Renewable and Sustainable Energy Reviews 59 (2016) 352–378

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Life cycle assessment (LCA) – from analysing methodology development to introducing an LCA framework for marine photovoltaic (PV) systems

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ARTICLE INFO

Article history:
Received 8 December 2014
Received in revised form
5 November 2015
Accepted 15 December 2015
Available online 21 January 2016

Keywords:
Life cycle assessment
Methodology development
LCA framework
Marine PV systems
ISO 14040
ISO 14044

ABSTRACT

Previously, life cycle assessment (LCA) focussing on principles or applications has been considerably reviewed. Still, an up-to-date review on LCA methodology development (rather than application) in a chronological order which embraces all life-cycle phases is lacking. The objectives of this article include scrutinising methodology development of conventional LCA phase by phase, providing clarification on goal and scope definition and life cycle inventory (LCI) analysis, discussing recent substantial development on life cycle impact assessment (LCIA) methodology and interpretation, and introducing an LCA framework for marine photovoltaic (PV) systems. For the study presented here, literature on LCA methodology development was categorised into Sample Groups A, B and C, comprising 15 review articles published in the last decade, 95 pieces of other literature types (with 83% journal articles), and 38 additional materials necessary for complementing an in-depth discussion respectively. A threefold analysis was performed to scrutinise and compare the literature in these sample groups. The analysis shows that for Sample Group A, the focus has steered from overarching LCA of all-embracing life cycle phases to single phase and then sole engagement with a specific topic; and for Sample Group B, 44% has reported the scientific endeavour on LCIA compared to other life cycle phases. Following clarification on system boundary, cut-off and existing LCI approaches including attributional, consequential, process based, input–output (IO) based etc., the methodology development of impact categories (covering impacts of water use, noise and working environment), uncertainty and sensitivity analyses are discussed. In addition, classification involving series and parallel mechanisms, LCIA development for space use, odour, non-ionising radiation and thermal pollution, rebound effects, renewability of resources, dynamic of environment and future scenario modelling in LCA context are identified as research needs and areas for future development. In compliance with ISO Standards and based on the findings, an LCA framework for marine PV systems (which exemplify the state-of-the-art development of renewable and sustainable energy in marine industry) is introduced to enhance the practical applicability and usefulness of the findings to LCA researchers.

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http://dx.doi.org/10.1016/j.rser.2015.12.058
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1. Introduction

Previously referred to as 'cradle-to-grave assessment' i.e. from acquiring raw materials, manufacturing and using to returning back to the earth, life cycle assessment (LCA) has been practised since the early 1970s to assess the environmental impact of a product, either goods or service, throughout its life cycle [1]. Aiming to introduce a universal technique which could be widely used to address the potential environmental impacts associated with a product, the International Organisation for Standardisation (ISO) introduced the principles, framework and basic requirements of handling each LCA phase in 1997 [2]. This was extended in the late 90s and beyond for the four LCA phases, including goal and scope definition and life cycle inventory (LCI) analysis [3], life cycle impact assessment (LCIA) [4] and interpretation [5], which were then revised and replaced by two shorter but more succinct documents, ISO 14040 and ISO 14044 [6,7]. An elaboration of the historical development of the Standards can be seen in [8,9], in addition to a summary of changes reported by [10].

The following conclusion made by [9] deserves further investigation:

> …*critiques of the ISO 14040 series has markedly dropped off since its redrafting and consolidation in 2006. Indeed, some recommendations are merely repetitions of similar arguments made previously or remain unsuitable*…

The nonexistence of persistent critique, even if it was the case, does not necessarily indicate acceptance or satisfaction. A possible explanation is that neither new ideas nor solutions have been proposed while the research community has become tired of the persistent problems. Indeed, some issues associated with the ISO 14040 series have been reported by [11–14] after the revision, including its overly flexible nature, the absence of step-by-step guidelines, the unequal level of detail, the legitimacy of the results as well as the lack of consistency and quality assurance, to name but a few. If recommendations are repeated, do they not imply a possibility of unresolved issues? Also, it is unclear which recommendations are 'unsuitable' in this context as no elaboration has been provided. If the claim (that the critiques have dropped off after revision) holds true – which it does not – it will be intriguing to find out if LCA, which is the focus of the Standards, has also become mature and free of critiques too.

A number and variety of LCA reviews have been published, either focussing on principles, challenges and opportunities [8,12,15–26] or covering LCA applications for materials [27,28], buildings and construction [29–34], food [35], transport [36,37], energy sources (such as bioenergy [38–45], solar [46–49], wind [50–53] and geothermal [54]) and electricity generation [55–57]. This does not repudiate but intensify the need of this article because an up-to-date analysis on LCA methodology development (rather than application) embracing all life-cycle phases is still lacking while it is intriguing to find out if LCA has become mature. To date, no one has ever attempted to review existing review articles. Also, integrating concepts/approaches proposed for a particular topic and clearly showing research development trend in a chronological order are missing. Therefore, this article aims to provide an up-to-date analysis on LCA methodology development covering 4 life-cycle phases. The following objectives are set:

- scrutinise LCA methodology development phase by phase to compare and integrate the proposed concepts or approaches;
- clarify goal and scope definition and LCI analysis;
- discuss LCIA methodologies for impact categories that have recently shown substantial development;
- detail methodology development with respect to life cycle interpretation; and
- introduce an LCA framework for marine PV systems based on the analysis.

The focus of this article lies on methodology development of conventional LCA embracing the four life cycle phases. In this article, a threefold analysis was developed (Section 2) as opposed to a commonly used one-off approach, followed by a presentation of analysis outcome (Section 3). From the analysis, areas are identified for discussion. Section 4 clarifies additional dimensions proposed for cut-off and system boundary selection in relation to goal and scope definition. Clarification on LCI is also provided to cover (i) the choice of attributional and consequential approaches dependent on what processes to include; and (ii) the integration and comparison of process based, fuzzy matrix based, input–output (IO) based, tiered hybrid, IO based hybrid and integrated hybrid approaches in accordance with data sources and fundamental principles. Methodology development of the identified impact categories (namely the impacts of water use, noise and working environment) with respect to LCIA as well as uncertainty and sensitivity analyses for life cycle interpretation are discussed extensively. Based on the analysis, research needs are highlighted. To enhance the practical applicability and usefulness of the findings to LCA researchers, an LCA framework for marine photovoltaic (PV) systems is introduced in Section 5 prior to drawing conclusions in Section 6. PV systems are chosen as they exemplify the state-of-the-art development of renewable and sustainable energy in marine industry. This article demonstrates that literature analysis can be applied in a comparative, interesting and practical way. It is believed that the new threefold analysis presented in this article can enhance the research quality of a wider research community as well as stimulate the understanding and practice of the readers focussing on LCA studies in marine industry.

2. Focus and methodology

In the form of a mind map, Fig. 1 illustrates not only the LCA phases – the core of the LCA framework as recommended by ISO 14040 [6], extending to the associated components and/or elements – but also the focus of this article (recognition, clarification or extensive discussion respectively presented in an off-white, grey or dark grey box). Other types of LCA study based on exergy, emergy, embodied energy or sustainability concept (see [33,58–61]) have been emerging. Although interesting, neither ISO 14040 nor ISO 14044 has included any of these concepts. Therefore, they are excluded from the analysis presented here, which will direct attention towards conventional LCA only.

Literature on LCA methodology development available on ScienceDirect and Google Scholar was identified for the analysis presented in this article. To uncover research trends shown by review articles and other literature types, including research articles, technical reports, guidelines, conference papers etc., a threefold analysis (instead of a one-off approach) was developed in 3 stages. In the first stage, 15 review articles published in the last decade (inclusive) were categorised into Sample Group A and analysed to determine their literature coverage in terms of topics and level of detail. In the second stage, 95 pieces of other literature types on conventional LCA study (with 83% journal publications) were selected to form Sample Group B and analysed to reveal the research trend. Upon completion of this stage, topics requiring clarification or recently being substantially developed were determined. In the third stage, literature in Sample Groups A and B was checked – additional literature materials, 38 in total which were necessary for complementing an in-depth discussion, were categorised into Sample Group C and analysed. Sample Group C was deliberately not added to Sample Group B to avoid any bias in the research trend. Separate disclosure and a comparison of the topics being covered by both review and other literature types were made possible through this threefold analysis to determine if they are in agreement. Based on the findings, research needs in the area of LCA are identified, followed by an LCA framework proposed for marine PV systems in compliance with ISO Standards.

3. Findings of literature analysis – the current research trend

3.1. Analysis of review articles (Sample Group A)

The outcome of analysing 15 review articles [8,9,12,15–26] is summarised in Table 1 where a scale of I–VI is adopted to describe

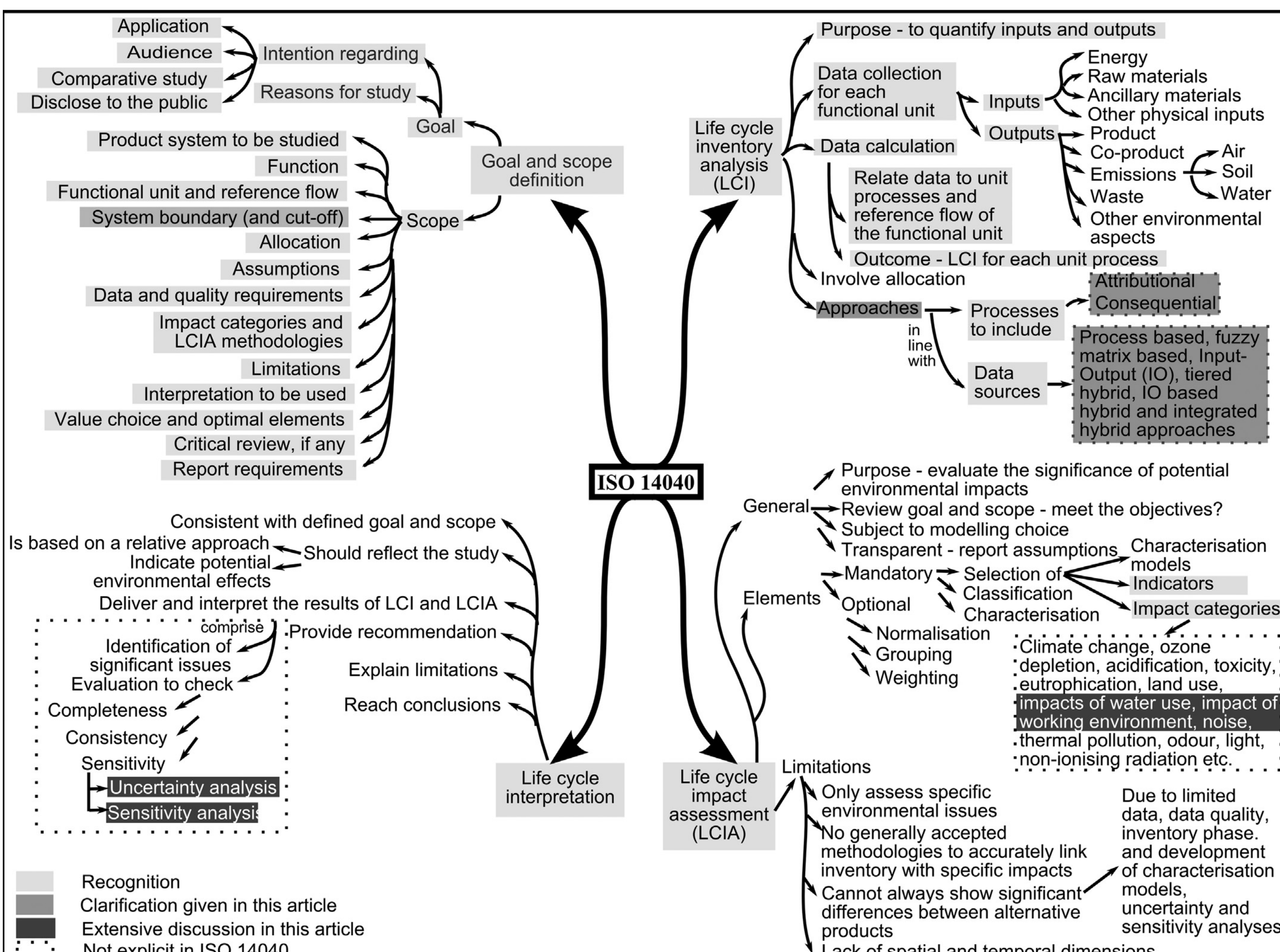

Fig. 1. A mind map illustrating LCA phases, elements and components in accordance with ISO 14040 and the focus of this article.

the level of discussion (from I which is for recognition to VI which is for extensive and integrated discussion). It was found that the articles have shown a research trend in accordance with life cycle phases. With the identification of research needs and challenges [8,25], the focus has steered from an overarching LCA concept of all-embracing life cycle phases [15,16,18–20], and then single phase of LCI [17] and that of LCIA [12] to sole engagement with a specific topic, e.g. consequential LCI [21], weighting [23], ISO Standards [9] and recently under-developing impact categories [22,24,26]. In relation to LCIA methodology development, the scope has become more specific in a similar manner, shifting from a wide range of common impact categories [15] and characterisation models [12] to a coverage of a few underdeveloped impact categories [20], followed by concentration on individual impact categories [22,24,26].

Among all, [20] presents the most comprehensive coverage, although transparency, documentation, temporal differentiation and sensitivity analysis are barely recognised while ISO standards, double counting, cut-off, serial and parallel mechanisms and dynamic of environment have been missed out. Conversely, [17,22] show the most limited scope with an emphasis on LCI and LCIA respectively. While data availability, source or database and uncertainty are most frequently recognised, characterisation and its methodology are most intensively discussed. A continuous coverage has been observed for most topics with the exception of process-based and hybrid LCI approaches, selection of impact categories, characterisation models and factors, and dynamic of environment, which have been exclusively unattended to since 2010. Meanwhile, some topics which are briefly mentioned in ISO 14040 and/or ISO 14044 are not at all or sporadically discussed e.g. serial and/or parallel mechanisms, recycling, future scenario modelling and grouping; other topics which are not included in ISO standards have been brought up e.g. rebound effect, renewability of resources, dynamic of the environment and consensus building or harmonisation. In addition, some topics, e.g. transparency and consensus building or harmonisation, are broadly recognised but not intensively discussed. Altogether, these findings reveal potential topics for further investigation.

3.2. Analysis of other literature types (Sample Group B)

In addition to ISO standards, overview, comparison and consensus building, those 95 pieces of other literature types in Sample Group B [1,6,7,10,62–152] are organised into 23 topics (representing the main focus of each) in accordance with life cycle phases from goal and scope definition to interpretation, as illustrated in Fig. 2. The country of the institution with which the leading contributor is affiliated and the year of publication are both disclosed. The main focus, publication type, objective and highlights are summarised in Tables S1–S6 of the Supplementary material. For literature which covers 2–3 main focuses, they are included under the relevant tables. A slightly different approach is adopted for those presenting

Table 1
Topics presented in review articles (Sample Group A) and the level of discussion.

Topic	Resource															Frequency (brief discussion: in-depth discussion)
	[16]	[15]	[17]	[12]	[18]	[19]	[20]	[8]	[21]	[22]	[9]	[23]	[24]	[25]	[26]	
ISO standards	IV	II	V	III	II			III			VI	III	I			9 (6:3)
Transparency	III			III	I		I	I				III	I	I		8 (8:0)
Phase I - Goal and scope definition	IV	III		I	IV	II	III	I			III			I		9 (7:2)
Functional unit	IV	III		I	IV	III	III				III				I	8 (6:2)
System boundary	VI		V		V	I	V		III	III	III		I	III		10 (6:4)
Phase 2 - LCI																
Allocation	I				IV	III	V		I		III	I				7 (5:2)
Multi-functionality	IV				V	I	II				I					5 (3:2)
Double counting			III		I	V									I	4 (3:1)
Recycling	III	I			VI		III	I	III		III			II	II	9 (8:1)
Rebound effect**							II		VI					I		3 (2:1)
Renewability of resources **							III						III		IV	3 (2:1)
Cut-off	I				VI	I					I					4 (3:1)
Attributional vs. consequential	IV				I		IV		IV				I			5 (2:3)
Data																
Availability/source/database	I		III	III	III	III	IV	III	I	III	I		IV	II		12 (10:2)
Quality	I	II	II	I	III	IV	III	IV			I			I		10 (8:2)
Documentation	IV			I	I		I						III		I	6 (5:1)
LCI approach																
Process-based	IV		V		V		V									4 (0:4)
Input-Output (IO) based	IV		V		V		V						I			5 (1:5)
Hybrid	IV		IV		V		V									4 (0:4)
Phase 3 - LCIA (mandatory)																
Selection of																
Impact categories		I		VI	I	IV	II	III								6 (4:2)
Category indicator		II		I	I	V	II	III		IV		I	III			9 (7:2)
Environmental mechanism^{+}				III		I	V^{+}	I					IV^{+}			5 (3:2)
Characterisation models/factors		I		V		V	VI	III								5 (3:2)
Classification		I			I	V	III	IV			I	I	III			8 (6:2)
Serial mechanism																0
Parallel mechanism																0
Characterisation		IV		VI	III	VI	VI	IV	II	III		I	VI		IV	11 (4:7)

Table 1 (*continued*)

Methodology		IV[a]		IV[b]		II[c]	VI[d]	VI[e]		IV[f]			IV[g]		IV[h]	8 (1:7)
Midpoint vs. endpoint		VI		IV		III	IV	III		III			IV		III	8 (4:4)
Spatial differentiation		IV		III	I	V	IV	III	I	VI			III	II		10 (6:4)
Temporal differentiation		IV		III	I	IV	I	III	II	VI			I	II		10 (7:3)
Dynamic of environment**					I	V										2 (1:1)
Future scenario modelling*					V		IV							I		3 (1:2)
Consensus building/harmonisation**	I	I		III	I	III	III	III	I				III	I	I	11 (11:0)
Phase 3 - LCIA (optional)																
Normalisation		IV		V		III	II	IV			I	III		I	I	9 (6:3)
Grouping		IV					III	V								3 (1:2)
Weighting		IV		V	I	IV	IV	V			I	VI	I	I	I	11 (5:6)
Phase 4 - Interpretation																
Uncertainty	I	IV		I	III	IV	IV	III			III	I	II	I	I	12 (9:3)
Sensitivity analysis	I				I	VI	I				I		I			6 (5:1)
Uncertainty analysis	I					IV	VI	III				I		I		6 (4:2)
Frequency	20	19	8	20	29	26	34	22	10	8	15	10	20	15	12	

[+] Environmental mechanism is shown in the literature.
* Implicitly included in ISO.
** Not included in ISO.
I Recognition, mentioned once or twice throughout the literature.
II Brief discussion, presented in a few sentences or a paragraph.
III Brief discussion, mentioned dispersedly 3 times or more throughout the literature.
IV Extensive discussion, in one stand-alone subsection.
V Extensive discussion, combined with other relevant topic(s) in one subsection.
VI Extensive discussion, integrated with other relevant topics throughout the literature.
A grey box denotes extensive discussion with a scale of IV, V or VI.
[a] Existing models and corresponding indicators are summarised for climate change, stratospheric ozone depletion, acidification, aquatic eutrophication, terrestrial eutrophication, human toxicological effects, ecotoxicological effects, photooxidant formation, biotic resources, abiotic resources, land use impacts, and other physical interventions, i.e. ionisation damage and nuisance from odour and noise including traffic noise.
[b] The characterisation approach of CML, Eco-indicator 99, Ecoscarcity, EDIP 97, EPS 2000, IMPACT 2002+, LIME and TRACI in assessing the damage of corresponding impact categories on 3 AoPs (i.e. human health, natural resources and natural environmental quality) are compared at midpoint, endpoint, damage and weighting levels.
[c] Existing models including CML, Eco-indicator 99, EDIP97 and TRACI are briefly discussed.
[d] Current LCIA development assessing abiotic resource depletion, impact of land use, impacts from water use, toxicity and indoor air are presented.
[e] Existing characterisation models and research needs respectively for global warming, ozone depletion, acidification, eutrophication, smog formation, land use, water use, human health and ecotoxity are briefly presented.
[f] Existing LCA approaches on soil-related impacts are briefly discussed.
[g] Existing LCIA approaches which assess the impacts of freshwater use at midpoint and endpoint levels are evaluated with an established set of criteria.
[h] The methodology approach adopted by Exergy, CML 2002, Eco-Indicator 99, EDIP 97, EPS 2000, IMPACT 2002+ and ReCiPe for assessing the impact of natural resource depletion at midpoint and endpoint levels are discussed.

an overview – instead of breaking down into subtopics, they are categorised under the umbrella of ‘overview’. Among all, 10 pieces of literature are published before 2000; 12 between 2000 and 2004 and the rest follow afterwards. Irrespective of literature presenting an overview, the majority have devoted to one main focus where approximately 16% covered 2–3 main focuses.

In brief, there are a number of interesting points to note: Netherlands, US and Switzerland, are the top 3 countries producing approximately half of the literature in this sample group. In contrary, LCA appears to be a comparatively new research topic in Asia where only 1 publication is from China, Japan, Philippine and Singapore each. Taking all into account, overview is the most common focus, followed by LCI approaches and LCIA methodology development for characterisation factors. The least attended subtopic in this part is not identified as those providing an overview are not broken down into subtopics. Research advance on LCI has been expanding gradually where new ideas such as water categorisation, consideration of capital goods, dealing with traffic noise, handling double-counting in tiered hybrid approach, and the use of fuzzy numbers, physical Input–Output Tables (IOT) and non-local data for LCI development are reported. Among all life cycle phases, the scientific endeavour on LCIA is relatively more prominent in which 44% of literature have respectively reported the development of framework, impact categories, indicators, characterisation factors, characterisation models and methods, classification, spatial and temporal dimensions, normalisation and weighting. The development of some characterisation models i.e. ReCiPe, IMPACT 2002+, TRACI, USES-LCA, USEtox and USES-LCA are reported, which is crucial not only to guarantee transparency but also to enable full understanding and appropriate practice among the users. Examples of recently addressed indicators and impact categories included soil quality, land as a resource, traffic noise, impact of work environment, impact of water use (freshwater ecotoxicity) and impact of resource scarcity. Research on some subtopics, such as sensitivity and uncertainty analyses, normalisation and weighting for LCA studies are slowly but steadily developed particularly in recent years. In relation to rebound effect, consensus building, serial and parallel mechanisms relevant to classification, recycling, future scenario modelling and grouping, the findings are in agreement with that of Sample Group A.

4. Discussion on LCA methodology development

From the results, one can interpret that methodology development of each LCA phase is not evenly balanced. From goal and scope definition to life cycle interpretation, there is an increase in complexity which comes along with diminishment in methodological advance. As the most straight-forward phase, goal and scope definition has received criticism to the minimal extent compared with the other LCA phases. Methodology for LCI has been more established than LCIA and life cycle interpretation. Extensive discussion on goal and scope definition as well as LCI is therefore not the focus of this article but only a few points requiring clarification to enhance the understanding of existing LCA knowledge. In relation to LCIA, attention is given on the methodology development of impact categories being substantially developed recently, including the impacts of water use, noise and working environment.

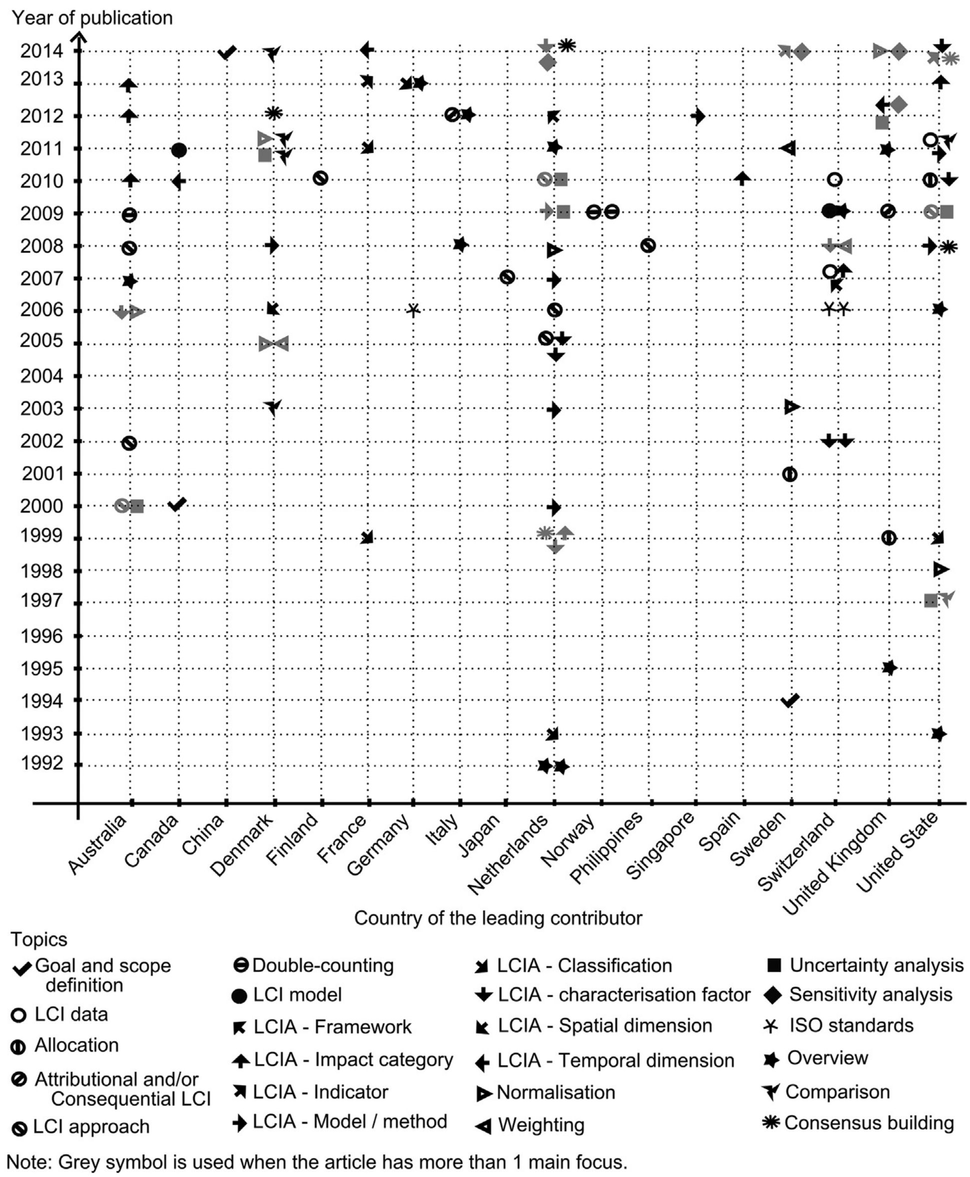

Fig. 2. The distribution of literature materials in Sample Group B.

Other impact categories are not discussed in this article not only because of the word constraints, more importantly, they are either hitherto more developed (e.g. climate change, ozone depletion, particulate matter formation, acidification, photochemical oxidant formation, human toxicity, ecotoxicity and resource depletion) or have not been substantially investigated (e.g. space use, odour, light, non-ionising radiation and thermal pollution). Regardless of how important and interesting normalisation, grouping and weighting (i.e. the optional LCIA elements) are, they are excluded from discussion due to the same reasons. In respect of life cycle interpretation, uncertainty analysis is extensively covered in line with its steady development in recent years, together with a discussion on sensitivity analysis for potential methodology development in the context of LCA due to its increasingly important role.

4.1. Goal and scope definition – ISO requirements, cut-off and system boundary

Goal and scope definition is of unquestionable importance as the primary phase of an LCA study. In defining the goal of an LCA study, it is required to clearly report the reason(s) for carrying out the study, the intended application and audience, the intention to use the results in comparative assertions and to disclose them to the public [6,7] (see Fig. 1). With respect to scope definition, it is required to clearly detail the study, including the product system to be studied, function, functional unit, reference flow, system boundary, allocation, assumptions, requirements on data and its quality, impact categories, LCIA methodologies, value choice, optional elements, limitations, interpretation, use of critical review and report requirements. In principle, deciding which stages (gate-to-gate, cradle-to-gate or cradle-to-grave), processes and elementary flows to include in an LCA study is known as system boundary definition where mass, energy and environmental relevance have been established by [6,7] as the cut-off criteria used to exclude any insignificant inputs, outputs or unit processes from a study. As summarised in Table 2, these topics have been broadly covered from recognition, discussion to application. As it is unlikely to know in advance which data is insignificant and can be excluded, additional dimensions have been distinguished by [18,20,62–64,68], as shown in Fig. 3. Particularly for boundary selection between different systems, a few methods have been reported as follows:

- Define the contents of the system either by process tree system [64], technological or social-economic whole system [62] – the process tree system only considers processes and transports which are directly involved in the life cycle of the system under study; the technological whole system accounts everything affected by the choice between comparative systems except economic and social forces which are included by the socio-economic whole system.
- Consider only the 'main' life-cycle stream – this method does not allow boundaries to be repeatedly selected, nor does the selection of similar boundaries for different systems [63].
- Set a percentage of the total mass, generally 5–10%, of unit processes in the system under study as the cut-off ratio to eliminate any input below the ratio – this method does not consider the impact of an input on its system from an entire life cycle perspective.
- Include only inputs which are readily available – this method can result in a false sense of completeness and bias analysis [63].
- Use alternative cut-off criteria by taking weight, energy, toxicity and price into accounts in defining the contribution of an input to the system as negligible, small or large issues regarding unrepeatable boundaries remain unsolved [63].
- Consider the relative contribution of mass, energy and economics to the functional unit which allows similar boundaries to be selected for different analyses – any non-energy-non-combustion related air emission is beyond the scope of this method [17,63].

Table 2
Literature coverage on goal and scope definition, system boundary and cut-off.

Topic		Coverage level
Goal and scope definition	I	[8–10,12,17,23,65,68,69,72,73,95,97,100–102,109,110,113,118,126,131,132,140,146]
	II	[15,19,25,64,75,79,96,128]
	III	[6,7,16,18,20,70,134,135,137–139,143]
	IV	[98,149]
System boundary	I	[24,68,79,80,82,83,89,98,111,113,124,126,140,141,144,146]
	II	[9,10,12,21,22,25,74,75,78,110]
	III	[1,6,7,16–20,62–64,70–73,129,134–139]
	IV	[94,121]
Cut-off	I	[9,16,19,21,76,81,82,104,132,139]
	II	[6,68,134,140]
	III	[7,17,18,63,64,70]

I Recognition where the topic is brought up once or twice.
II Brief discussion where the topic is mentioned 3–5 times, discussed slightly without much detail.
III Noticeable discussion where the discussion of the topic is either in a dedicated section or integrated with other topics throughout the literature.
IV Case study.

It is important to point out that selecting appropriate system boundaries generally requires a large amount of data which results in additional cost and time [18]. Due to its considerable impact on "the depth and the breath of LCA" [6,7], goal and scope definition (including system boundary and cut-off) is a decisive factor to determine the credibility of LCA results. Without due care, any omission or flaw at this fundamental phase will result in an absolute divergence due to a sort of snowball effect, leading to misinterpretation and inappropriate decision.

4.2. LCI

4.2.1. Attributional and consequential approaches – clarification on what processes to include

Without much detail, ISO 14040 [6] has added the following remark in its annex:

Two possible different approaches to LCA have developed during the recent years. These are

(a) *One which assigns elementary flows and potential environmental impacts to a specific product system typically as an account of the history of the product, and*
(b) *One which studies the environmental consequences of possible (future) changes between alternative product systems.*

A few terminologies have been adopted for these approaches: the former is referred to as attributional (most common), descriptive, accounting or retrospective LCA while the latter is known as consequential (most common), prospective, change-oriented, decision- or market-based LCA [11,20,72]. Similar to goal and scope definition, attributional and consequential LCA have also been broadly studied, from recognition [18,24,64,81,144] to brief [80,141,143] and noticeable discussions [16,20,21,67,70–72,138,139]. The core subjects of discussion in this regard are presented as the following:

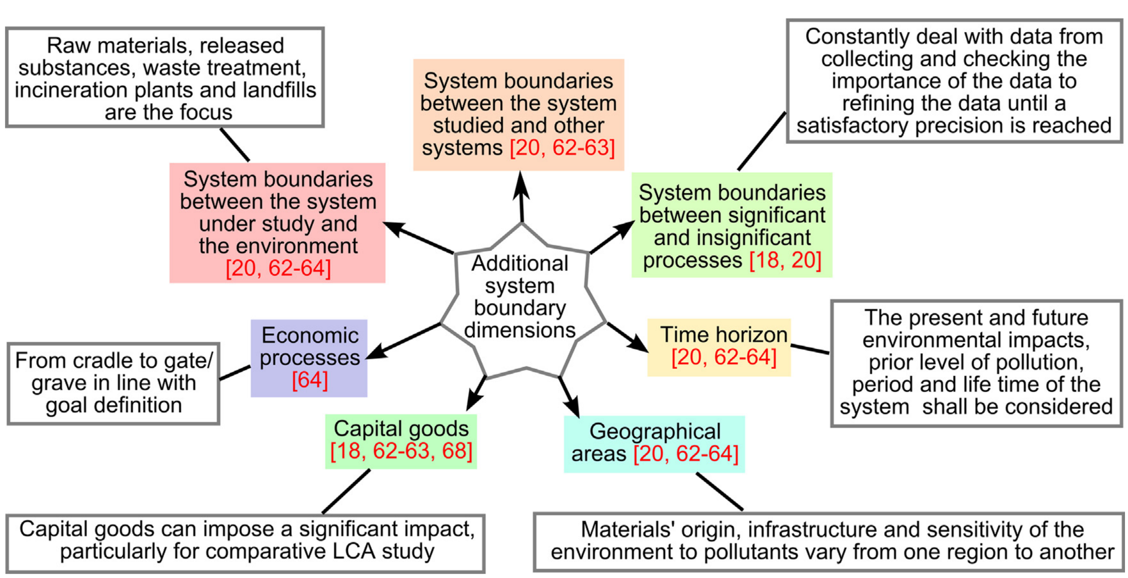

Fig. 3. Additional dimensions for cut-off and system boundary selection.

(i) The use of average or marginal data. A distinction is presented in accordance with attributional and consequential approaches, see [16,21,70,71,137]: attributional LCA uses average data (which are measured, historic or fact-based) to account for inputs and outputs that are directly involved in production, consumption and disposal of the product system under study at a specific time and particular production level which deliver a certain amount of functional unit without considering market and non-market effects in which the inputs and outputs are generally allocated based on mass, energy content or economic value. In contrast, consequential LCA uses marginal data (which involves a generic supply–demand chain built upon a decision) to account for all inputs and outputs that significantly, directly and indirectly affected by a change in the production of the product system due to the substitution or use of constrained resources etc. by taking into account both market and non-market effects (e.g. policies and impact of research and development) in which allocation is avoided via system expansion.

(ii) Deciding between attributional and consequential approaches. According to [72], the choice can be made by answering some questions, as listed in the following:

- How is system boundary of the study defined?
- What are the processes to be included?
- What are the causal chains to be used?
- How are questions framed to identify the exact problem to be tackled?
- What are the derived questions?
- What are the technological options?
- What is the scale of the expected change(s)?
- What is the time frame of the question?
- Can a ceteris paribus assumption be held?
- Is the system under study replacing another system on a small scale?
- Is the technology used in the new system expected to extend to other applications on a larger scale?

Considering the equivocal and wearisome nature of this method which indeed presents an evident shortcoming, one may alternatively consider a three-question provisional scheme proposed by [138] as illustrated in Fig. 4. However, it is important to point out that, as according to [138], the scheme is immature and a further in-depth testing is required as it is merely the first step towards building a consensus among LCA community. In this matter, [20,21,139] report that no consensus has been reached among LCA community on the appropriateness of one approach compared to the other, relevance of the knowledge generated by both approaches and their practicability.

(iii) Whether to combine attributional and consequential approaches – while [72] notes that consequential LCA has always been inconsistently performed and misinterpreted as 'the state-of-the-art methodology', [71] strongly claims that both approaches must stand alone where a combination is not allowed. Dissimilar recommendations are given by [16,20,72], leading to a confusing situation. An emphasis shall be made on the fact that both approaches serve different purposes, as implied by [6] (as mentioned earlier). To reiterate, attributional LCA aims to identify environmental burdens throughout the life cycle of a product system while consequential LCA estimates the change in environmental burdens incurred by a decision made in line with a marginal change in the production of that system. A clear-cut solution is therefore incontrovertible to the question of whether to combine attributional and consequential approaches if one refers to this very fundamental concept in practice based on the reason(s) of carrying out the LCA study. Such a simple but decisive approach is appropriate from a pragmatic point of view in line with the purpose of LCI (i.e. to collect and quantify data). As clearly pointed out by [72], the difference between both approaches is the type of processes to be taken into account (i.e. attributional approach considers processes which significantly contribute to environmental burdens; consequential approach accounts for processes which are affected by decisions) while their (LCIA) modelling principles remain unchanged. In addition, both approaches can be applied one after the other separately if an LCA study aims to serve more than one purpose, for example to compare the environmental impacts of a product system with an alternative system before and after implementing some technical improvements.

4.2.2. *LCI approaches – clarification on what data sources and principles to use for quantity computation*

The purpose of developing LCI is to calculate the quantities of inputs and outputs involved in delivering a specific functional unit of the product system under study [16], which typically produces a list of substances with identified quantity as the outcome. Based on data sources and fundamental principles used for computation involved in LCI compilation, a number of methods have

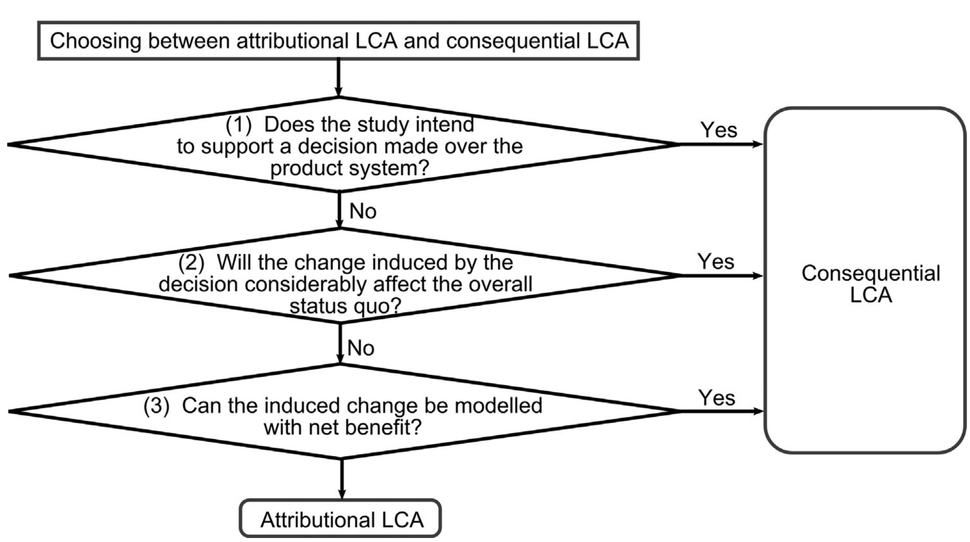

Fig. 4. The 3-question scheme provisionally used for choosing between attributional and consequential LCA, as proposed by [138].

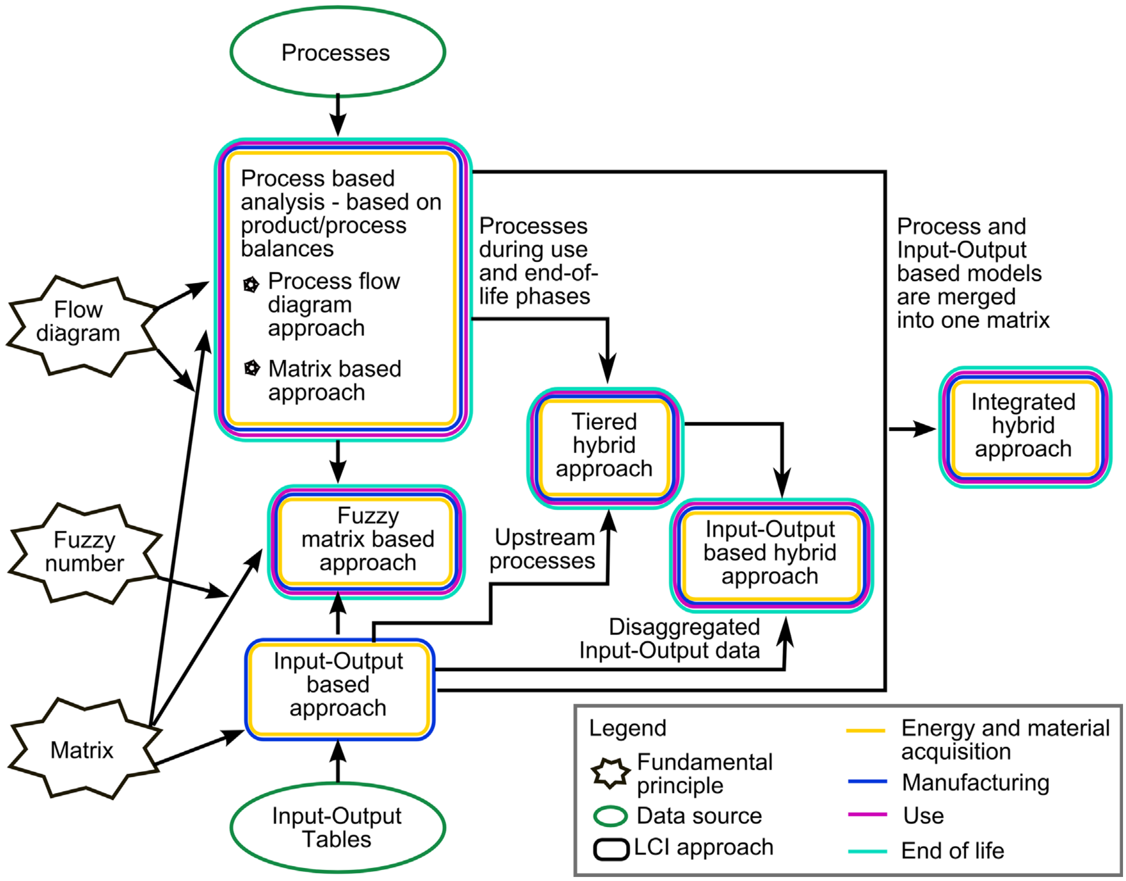

Fig. 5. Outline of existing LCI approaches in line with fundamental principles, data sources and life cycle phases.

been developed including process (using process flow diagram and matrix), fuzzy matrix, IO, tiered hybrid, IO based hybrid and integrated hybrid approaches. These methods have been respectively recognised [63,79,92,121,129,141,143,144], briefly [81] or noticeably discussed [16–18,20,64,67,70,74–85,134,135,137–139] or applied [78,82,133]. Fig. 5 presents an overall idea how these methods can be integrated among one another in line with fundamental principles, data sources and life cycle phases from energy and material acquisition to the end of life. [75] compares these methods (except fuzzy matrix-based approach) in terms of data requirements, uncertainty of data source, system boundaries, software tools and requirements of computation tool, simplicity, and the intensity of time and labour. Based on [16–18,20,64,73–82,85,133,137–139], Table 3 briefly describes the methods and extends the comparison to cover strengths and limitations of each method. The use of structural path analysis in hybrid LCA [74], although interesting, is excluded from this comparison because the analysis does not compile LCI but rather preliminarily identify the most important input paths. Along with the criteria proposed by [16,75] such as goal and scope, requirements on accuracy and level of completeness, time, budget and data availability, the strengths and limitations of each approach shall also be taken into consideration in choosing an LCI method in practice.

4.3. LCIA – recent methodological development

4.3.1. The impact of water use

Water has been considered as an abiotic resource since the early stages of LCA development. Somehow, the perspective has evolved to recognise water as an impact category due to its use and depletion. [12,15,19,20,24,26,87,95,142] are the articles in Sample Groups A and B which, at different levels of detail, consider water use as an impact category. In brief, [12,15,19,26] do not give much focus while [20] leaves out some important development. As a review focussing on freshwater use at LCI and LCIA levels, which presents a number of existing approaches, [24] is fully dedicated to the topic at the expense of other LCA elements. Research articles are limited to [87,95] and a case study is reported by [142].

The investigation reveals that additional resources, i.e. [153–161] (in which some are respectively built based on [162–170]) are necessary to present a more comprehensive scope, as illustrated in Fig. 6. Definitions of some terms, e.g. water source, flow, use, return and depletion, have been partially proposed by [87,153–155,157,158] and these have been integrated for water classifications as illustrated in Fig. 7. The general comments made by [12,15,19,20,24,26,87,95,142] and the methodological concept of the approach reported by [153–161] are briefly summarised in Table S7 of the Supplementary material. A few additional points are worth noting:

- In respect of water quality, 3 proposals are reported, respectively based on un-usable to excellent quality levels [87], distinction approach (i.e. distance-to-target method or water functionality) [157] and quality indicators [153]. As complexity increases from quality level, distinction approach to quality indicators, the incorporation of any quality indicator proposed by [153] into impact assessment methodology has not yet been achieved, except thermal factor being assessed by [159].
- Although approaches recommended by [155,156,170] have been applied by [142] in a case study to assess the impacts of water use, [142] does not point out that the indicator results from these approaches are not in agreement. Despite dissimilar result patterns and magnitude orders (as evidenced by the results reported by [142]), existing methods have not received any

Table 3
Brief description, strengths and limitations of LCI approaches.

Approach	Brief description	Strengths	Limitations
Process flow diagram approach [17,20,64,73–75,80,82,133]	• Apply bottom-up process analysis based on process and product balance models • Inventory is calculated with algebra; when required, infinite geometric progression can be applied to simplify the calculation	• Case-specific and more accurate • Most common form of LCI approach	• Time-consuming and expensive to collect empirical data or from other sources • Underestimation and truncation error occur when capital goods and upstream processes are cut off • Calculation can be complicated when the system involves multi-functionality or interconnecting inputs between processes • Subject to use outdated data
Matrix based approach (simplified model) [17,76,80]	• Similar to process flow diagram approach where simultaneous equations are created based on bottom-up process analysis using product balance or process balance. The equations are then solved by matrix	• Powerful • Able to solve endless regression problems associated with system and support advanced analyses, such as connections with IOT	• Restrict to single-output processes • Not clear if process balance can deal with multi-functionality issue • The number of processes to be included is still limited and capital goods are generally excluded
Fuzzy matrix based approach [79,81]	• Fuzzy number is integrated into matrix-based LCI at different possibility levels • Derive material composition matrix based on resources, materials and products; and make use of data from IOT	• Data uncertainty due to vagueness can be modelled at different possibility levels • Computational time is considerably short compared to Monte-Carlo model	• Cannot model correlated uncertainties • Determining fuzzy distributions of the inputs is complicated • Limit to inverse-positive matrices only
IO based approach [16–18,20,73,80,137,139]	• Matrixes are formed based on top-down monetary transactions among industry sectors as published in IOT, which are national data on the supply and consumption of goods and services	• Easier to perform. • Eliminate the need to estimate data for each process • Take account of capital goods • Transparent because only publicly available data and standard calculations are used	• Resolution is too coarse for detailed studies involving raw material selection, process redesign and any comparison at regional or international levels • Data are old, inconsistent (due to compilation variation) and with high aggregation level, leading to aggregation error • Cannot provide LCIs for the use and end of life stages • Cannot correctly reflect the environmental burdens as process data are not used for modelling
Tiered hybrid approach [17,20,73,75,77,78,85,138]	• Direct inputs to main processes are calculated with detailed process analysis while upstream flows that are indirectly connected to the main processes are estimated via IO based approach	• Combine the strengths of process and IO based approaches • LCI compilation is quick • Capital goods are included • Results are more comprehensive	• Suffer from double-counting unless material flow analysis is incorporated • Process and IO based approaches cannot be assessed together systematically
IO based hybrid approach [17,75,78]	• Also known as hybrid LCI method based on IO data • To improve process specificity, IO data on industry sectors are disaggregated and solved by tiered hybrid approach; process based approach is applied for main processes during use and end of life phrase	• Consistent • Higher resolution for detailed applications • Avoid double-counting	• Issues with process data and IOT remain the same • Difficult to model the relationship between life cycle phases of a product
Integrated hybrid analysis [17,75,138,139]	• Detailed information at unit process level is fully incorporated into IO model by linking process-based system (represented in a technology matrix by physical units) and the IO system (in monetary units) through flows crossing the border of both systems • Process and IO based approaches are integrated consistently into one matrix	• Double-counting is avoided as tiered hybrid approach is not applied • Consistent and complete for upstream processes • Interactions between processes and industries are fully modelled	• Complex • Time-consuming • Require intensive data

criticism – which is uncommon compared to the cases of other impact categories (e.g. acidification, eutrophication and eco-toxicity) generally assessed by different LCIA methods e.g. CML, ReCiPe, ILCD etc.. What is more, it remains a challenge to decide which concept to apply among existing methods.

- Although not elaborated here, research developed for other relevant subject areas (but not directly within LCA context), e.g. virtual water by [162,166], surplus energy concept by [168], water indices as recognised by [24] (e.g. water resource per capita, basic water needs, withdrawal- and consumption-to-availability, water poverty and groundwater sensitivity indices) and those for natural resources in LCA context, e.g. eco-factors applied in ecological scarcity by [170] and exergy by [169], have been or can be applied for LCA methodological development. Refer the supporting information presented by [24] to see the findings of scientific comparison among existing methods, covering completeness, robustness, relevance to environment, transparency, documentation and reproducibility, applicability and stakeholder acceptance.
- Data regarding quality requirements, use, availability, demand, vulnerability, scarcity, conflict, poverty index and future of water, if available, probably will be useful for developing and performing LCIA for this impact category.
- Research is required to further develop LCIA methods which can fully address water quality, temporal and spatial factors – a challenge to the LCA community.

4.3.2. The impact of noise

From cradle to grave, the life cycle of a product system involves an extensive number of processes. As pointed out by [134], “a process produces a certain amount of noise”. The impact of noise in LCA context has been conveyed in literature over the past

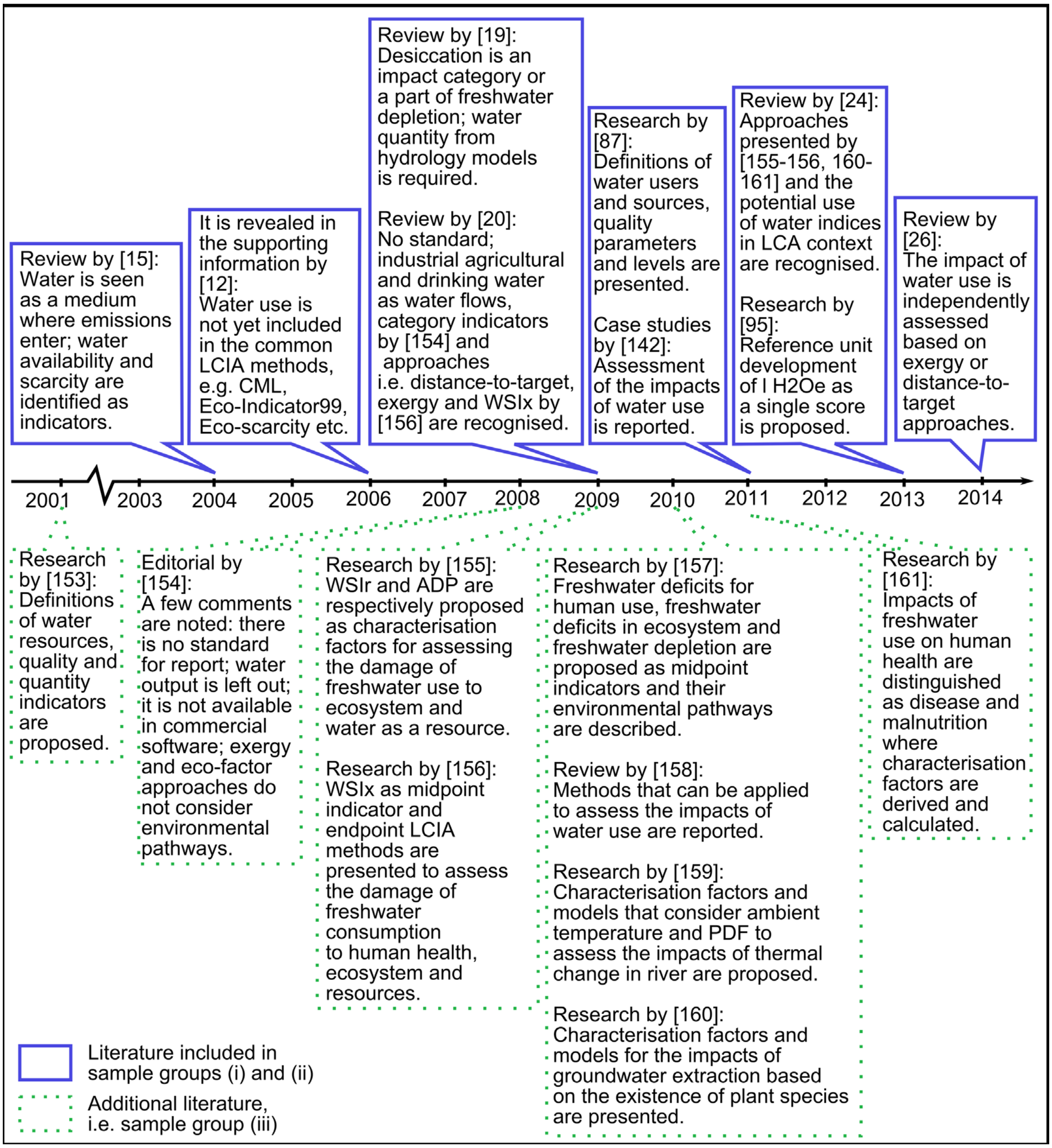

Fig. 6. LCIA research development in relation to the impact of water use.

2 decades, and possibly earlier, from simply recognising it [15,16,20,90,101,102,109,128] and commenting on its standing [12,19,25,101,104,131,144,151] to briefly discussing it [92,134,139] and fully developing a methodology for its impact assessment [86,89,93,120,171–176] (where [171–176] are literature included in Sample Group C to complement the discussion), as illustrated in Fig. 8. It is apparent that methodologies to assess the impact of noise have been rapidly developed [144] and become available [25]; still, it is neither included in LCI database [92] nor applied in most LCA studies [104,151]. By the means of additional tools (e.g. noise emission models, national databases, surveys, questionnaires and experiments), various concepts covering physics (e.g. sound energy), mathematics (fuzzy numbers/intervals and variation in noise level), social science (e.g. disturbance, nuisance and health damage), demographics (e.g. population density) etc. have been selectively applied in developing these methodologies. The concept of each methodology is summarised as follows and a comparison is presented in Table 4.

(1) Sound energy concept [134] which is also referred to as CML guide [176] – the method claims that noise is linearly generated with the process of manufacturing a product system. Therefore, noise production (in the square of sound pressure second, Pa^2s) can be determined by taking account of sound energy (in Pa^2, derived from sound pressure level in decibel, dB) and the duration in which noise is generated, together with hearing threshold and the quantity of required materials or products produced in a year.
(2) Disturbance and equivalent traffic concept [171], also referred to as Ecobilan method [176] – the method determines the noise thresholds for day- and night-time in accordance with legislation and measures disturbance which is expressed as the total number of people disturbed. Data on population density, existing mapping and noise propagation model (based on equivalent traffic concept which assumes that the potential noise impact of the traffic mode under study and that of a reference mode on the environment are the same) are used to measure the disturbance as per specific transport means.

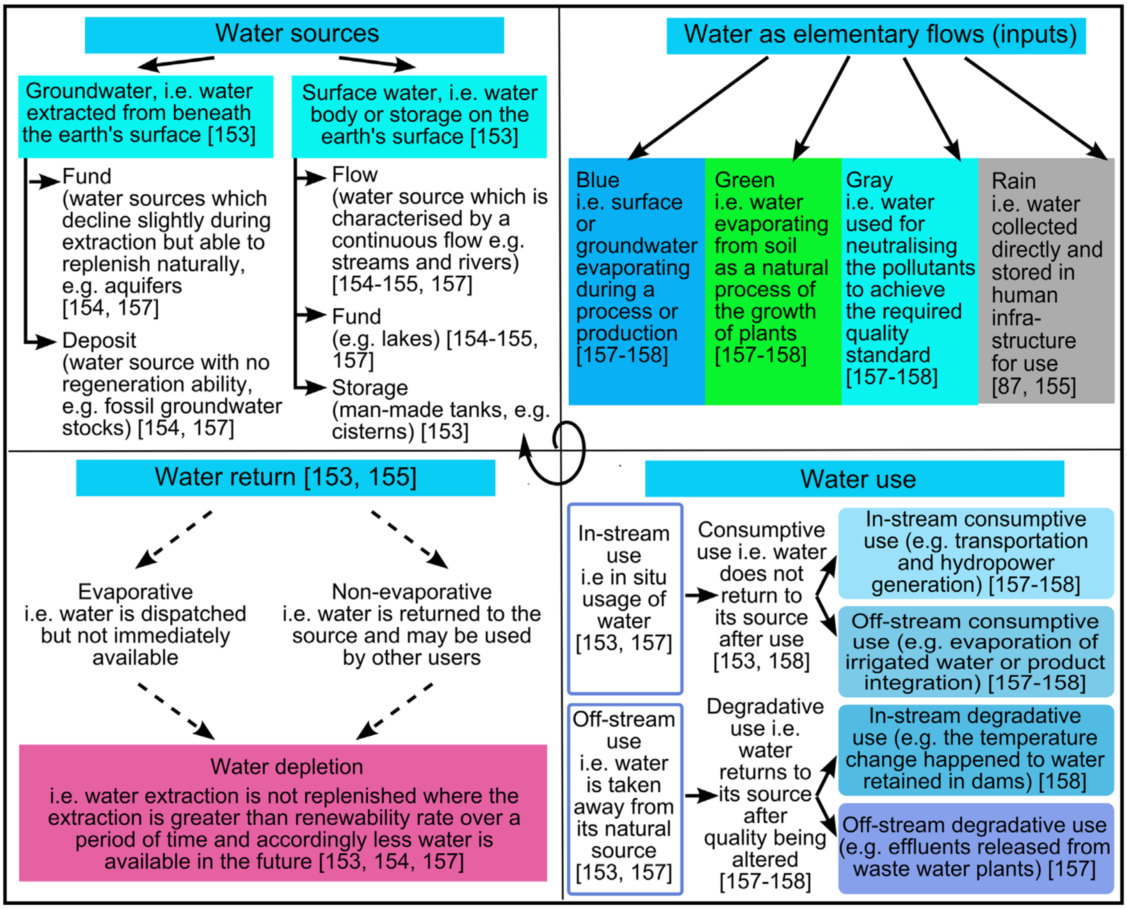

Fig. 7. Water classification as sources, elementary flows, use and return.

(3) Environmental scarcity factors or Swiss FEDRO method [176], also referred to as Doka methodology [175] – although [175,176] both claim that the method is adapted from the earlier work of Muller–Wenk (which is inaccessible), a variant of methodological concepts has been reported. According to [176], the Swiss FEDRO method determines the environmental scarcity factors by defining actual and critical flows based on people who are highly annoyed by the noise emission. The former is the number of highly annoyed people (derived from Swiss EPA method and the effect curves from Swiss survey) while the latter is set as 20% of Swiss population. According to [175], Doka claims that non-linear relationship exists between noise emission and its effects on human health; and therefore, to calculate the damage caused by noise emission in disability-adjusted life year (DALY) per vehicle-kilometre, noise emission that is measured in dB can be substituted into a simplified formula which incorporates regression parameters.

(4) Total nuisance caused by a specific process, also known as Nielsen and Laursen methodology [175] or Danish LCA guide [176] – in this method, information such as background noise and noise level (both in dB; the former is set via interviews and the latter is simulation results from noise emission and propagation models), process duration and the number of people (based on average population density) exposed to the noise produced in a process (in which transport is selected for the study) are required to determine the total noise nuisance caused by the process (in person-second).

(5) Fate-exposure-effect-damage model [172], also known as Swiss EPA [176] or Muller–Wenk methodology [175] – the method involves the following analyses via different approaches:

- Fate analysis – by taking account of vehicle types, speeds and gradient of a road and the use of the existing noise emission model i.e. SAEFL, the average noise level per year, Leq and the increase in noise level, ΔLeq resulting from increased vehicle numbers per year are determined.
- Exposure analysis – number of people exposed to the increased noise level can be extrapolated from the figures estimated by Kanton's road noise emission model.
- Effect analysis – relationship between communication disturbance at day-time (or sleep disturbance at night-time) and the noise level is determined based on the outcome of social surveys.
- Damage analysis – disability weight (DW) for communication and sleeping disturbances (which are determined based on responses collected from 41 physicians via questionnaire) are used to determine the health damage due to traffic noise, in DALY per 1000 vehicle-kilometre.

(6) Fuzzy-set approach [173] – after defining the quality of the sound environment i.e. types of land use (urban, residential or rural), population densities and noise level intervals in the form of fuzzy numbers, the overall noise level of a process can be calculated, which is necessary for the (dimensionless) impact assessment of noise based on nuisance felt by the population under study. In addition, the fuzzy-set approach can be incorporated with semantic distance concept to perform pairwise comparison upon the LCIA results of different impact categories across a range of scenarios, as demonstrated by [174] in assessing electricity generation processes.

(7) New framework to extend Swiss EPA method to specific vehicles, tires and situations [86] – the method is built on the

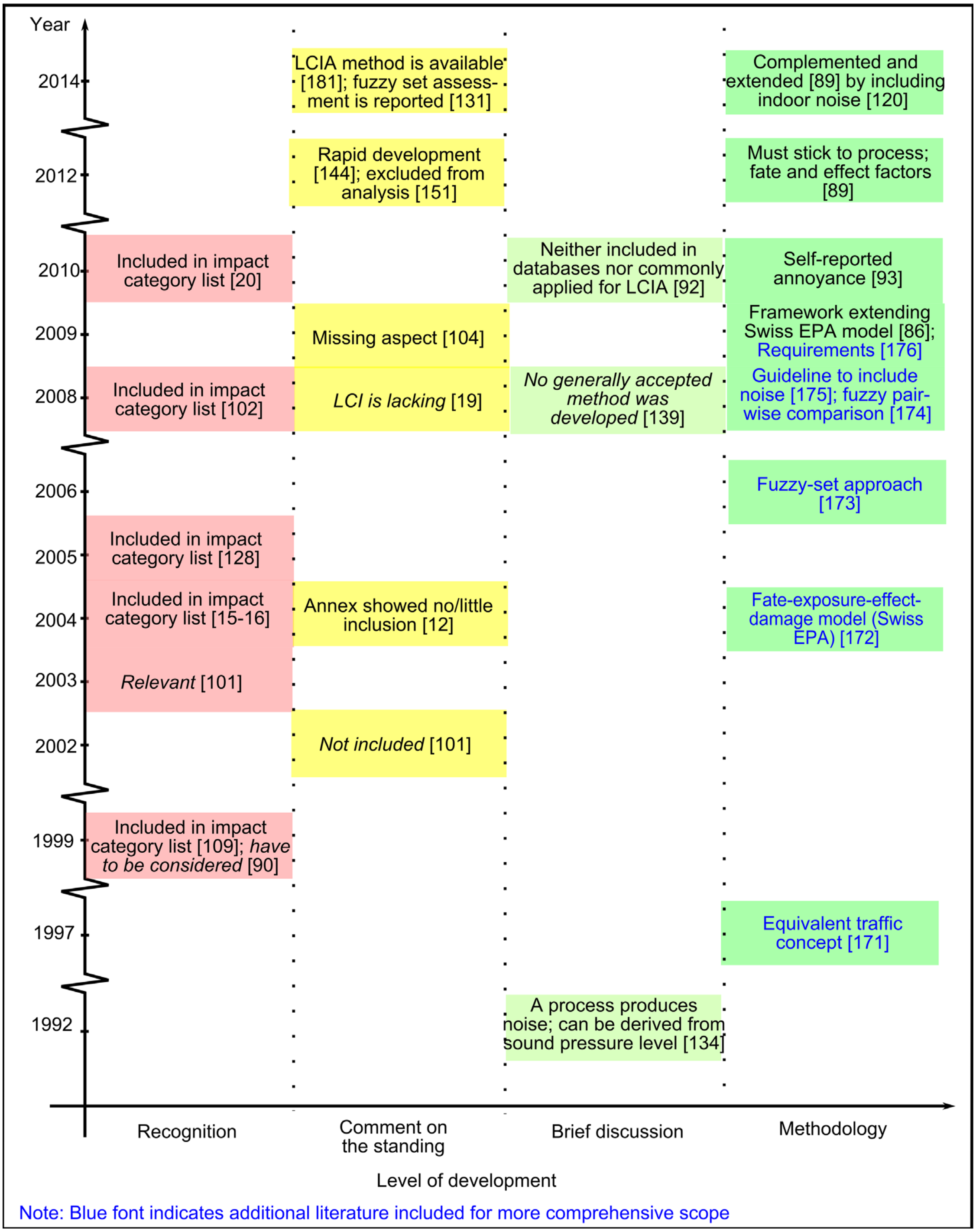

Fig. 8. Literature development on the impact of noise.

earlier work of Muller–Wenk to calculate the additional noise level resulted from an increased number of vehicles, where vehicle and tire types (using a noise emission model, i.e. SonRoad and TUV measurements respectively) as well as time and space are distinguished. The approach also takes into account population densities and differentiates road classes based on noise effects upon the population.

(8) Self-reported annoyance [93] – the method uses existing noise emission model i.e. IMAGINE to model traffic flows at 2 situations so that the variation in noise level (known as noise-relevant life cycle variations, NRLVs) can be determined. The number of highly annoyed persons is estimated by applying polynomial approximation to the dose-response functions. Based on the increased percentage of annoyance due to NRLVs, the impact can be estimated as the product of difference in the percentage of annoyance and the total number of people exposed to noise.

(9) Fate-effect model [89] – after pointing out the common deficiency of previous methodologies (i.e. fail to focus on the process that producing noise emissions rather than the situation in which noise takes place), [89] proposes a new methodology which defines the characterisation factors for noise impact category in LCA context as the product of fate and effect factors measured in person-Pascal per Watt. Fate factor,

Table 4
Comparison of existing methodologies for the impact of noise.

Concept (unit)	Source of noise	Spatial differentiation	Temporal differentiation	Use of specific parameter, tool or approach	Type of data required for calculation	Strengths	Limitations
Sound energy concept (the square of Pascal) [134]	Process [134]	No [176]	No [176] (although 'the time during which noise is generated is relevant' [134])	Threshold of hearing	Quantity required to meet the functional unit and annual production [134]	Comply with ISO 14040 and is applicable to all situations [176]; simple and straight-forward calculation	Only consider the aggregation of sound at midpoint level [12]; less useful and not suitable for comparison [176]
Disturbance and equivalent traffic concept (Number-of-people-hour/passenger-kilometre or number-of-people-hour/goods-kilometre) [171]	All transport modes or production plant [171]	Yes [176]	Yes [176]	Noise thresholds for day and night time; experiments to determine equivalent traffic coefficients [171]	Areas affected by noise above thresholds; distance of the source of noise from the ground and the presence of any obstacle between the source and the observer [171]	The results may be used as models to assess traffic noise in European countries with similar population density along the road under study [171]	Do not comply with ISO 14040 and the indicator is very rough [176]; cannot differentiate the sources of noise in the assessment as all are treated as 1 single source
Environmental scarcity factors [176] (DALY/vehicle-kilometre) [175]	Road traffic [176]	Yes [176]	Yes [176]	Regression parameters differentiated by the time of journey, i.e. day or night [175]	Noise measured in decibel [175]	Quite practical [175]; allow for intermodal comparison; comply with ISO 14040 [176]	Only address traffic noise
Total nuisance caused by a specific process (person-second) [175]	Process when goods are being transported [175]	Yes [176]	No [176]	Background noise relative to 20 μPa [175]	Number of persons and noise level within/at a distance from the source; duration and noise level [175]	Simple [175]; allow for intermodal comparison [176]	Do not comply with ISO 14040; not suitable for inclusion in LCI databases, and overestimate the noise effects [176]
Fate-exposure-effect-damage model (DALY/1000-vehicle-kilometre) [172]	Traffic [176]	Yes [176]	Yes [176]	Noise emission model for fate analysis; computer model for exposure analysis; survey for effect analysis, and questionnaire for damage analysis [172]	Traffic (i.e. average number of vehicles per type, speed and road gradient etc.) and demographics (i.e. population being exposed to the noise) [172]	Applicable to different countries [175]; comply with ISO 14040 and comparison to other impacts measured in DALY can be made easily [176]	The noise emission model is obsolete [175]; may overestimate noise effects [176]; inaccurate due to simplifications; only address traffic noise
Fuzzy sets approach (dimensionless) [173]	Any process (unit process and traffic noise are referred for conceptual discussion; example is given on coal mining and combustion processes) [173]	Yes	No	Noise level range, fuzzy numbers and intervals	Quality of site, (i.e. existing noise level; types of land use—rural, urban and residential; population density); nuisance felt by individuals and time exposed to the noise [173]	Uncertainty is accounted for by the fuzzy numbers [174]; can be applied to any process	Sophisticated and require expert judgement for determining variables of the assessment [173]
Guidelines for incorporating the effects of noise into LCA (DALY) [175]	Road traffic [175]	No	No	Model to stimulate virtual network of roads and vehicle fleet (e.g. IMAGINE); survey [175]	Noise maps, demographics data [175]	Potential reference for methodology development in the future	Methodology has not been developed for the impact assessment; limited focus on traffic noise
Requirements for methods used to incorporate noise into LCA [176]	Traffic [176]	Yes	Yes	–	–	Potential reference for methodology development	Methodology is not developed for the impact assessment; limited focus on traffic noise
New framework to extend Swiss EPA method (dB(A)) [86]	Traffic [86]	Yes	Yes	Vehicle-specific noise emission models (i.e. SonRoad and TUV) and correction factors [86]	Measurements of real traffic situations [86]	The results can be implemented in LCI databases for other LCA study [86]	Noise from mixed sources is not considered yet [86]; limited focus on traffic noise
Self-reported annoyance (number of annoyed persons) [93]	Traffic [93]	Yes	Yes	Traffic noise emission model (i.e. IMAGINE), health damage model, and incremental approach (to determine noise relevant life cycle variations, NRLVs) [93]	Traffic data (e.g. vehicle speed and flow etc.) and receiver data (e.g. demographics, frequency distribution of noise exposure, and background noise) [93]	Results are more accurate due to the state-of-the-art noise emission model; more intelligible for decision making [93]	Require intensive data, is limited to variation assessment where environmental impact of noise is not assessed [93]
Fate-effect model (person-Pascal/Watt) [89]	Processes [89]	Yes	Yes	Scale of sound frequencies (i.e. octave bands); sound power (in Watts); sound	Sound emission, weighting factors and number of people	Noise effects are related to functional unit and the methodology focusses on the	Despite the proposed methodology, characterisation factors are not presented and

Table 4 (*continued*)

Concept (unit)	Source of noise	Spatial differentiation	Temporal differentiation	Use of specific parameter, tool or approach	Type of data required for calculation	Strengths	Limitations
				power level (in decibel), using fate and effect models [89]	living in the compartment; directivity of sound [89]	process causing the noise rather than the situation where noise takes place [89]	therefore cannot be included into existing LCIA models straight-away
Fate-effect model [120]	Processes [120]	Yes	Yes	Raster maps (i.e. ArcGIS 10); fate and effect models [120]	Directivity of sound; sound power and sound power level [120]	Complement [89], provide characterisation factors for future LCA study; distinguish fate factors for noise emissions in internal (occupational) and external environments [120]	–

in Pascal per Watt, is determined at the background level as the small increase of sound pressure due to a marginal change of sound power at a compartment where directivity and attenuation (in line with a frequency scale defined by 8 octave bands) are taken into account. Similarly, effect factor, measured in person, is defined as the small increase in person-pressure due to a marginal change in sound pressure of an octave band at a compartment based on the number of people living in that compartment, the day-night weighting and the A-scale weighting (for the octave band). [120] complements the fate-effect model by not only presenting characterisation factors but also distinguishing the fate model for noise impact upon the internal occupational and external environments.

4.3.3. *The impact of working environment/impact related to work environment*

The impact(s) of working environment on human health has also been recognised since 2 decades ago as an impact category in LCA context. For instance, in the early 1990s, [134] already affirmed that there was no quantitative method developed to address such impact(s). Some similar and relevant aspects have been briefly set forth by [8,19,20,90,96,102,121,139,144,151] where different terminologies are adopted, including “accidents”, “working condition”, “working environment”, “indoor air”, “indoor air pollution”, “indoor and occupational exposure” etc. In brief, accidents are recognised as an impact category which is poorly developed with neither inventory nor characterisation factors being available [151]; related to work environment (caused by accidents or non-toxic substances) and shall be taken into account comparatively to human toxicity category [90]; indecisive whether the impacts of casualties attributable to accidents shall be seen as an individual impact category because of the absence of standards, and consequently, impacts attributional to work environment are generally out of consideration [19]; and therefore being omitted due to the difficulty in making prediction and the negligible effect as perceived [102]. In this matter, [8] indicates that indoor air pollution has already been included as a special application of LCIA where [20] claims that human exposures to indoor chemicals can be significant and LCIA is already available to assess such impacts on internal environment in line with the report of 2 relevant case studies. In terms of indoor and occupational exposure, [139] projects that it is to be considered as a part of human toxicity impact category despite the fact that it has been developed as a new impact category. The latter is in agreement with [144] who highlights the expeditious LCIA development for indoor and occupational exposure as a new impact category, which can be exemplified by [96,121].

Despite the recognition of the impact(s) related to work environment, none of the above mentioned literature has defined this impact category, as do [177–179] – which may explain the use of a variety of terminologies. However, it is commonly accepted that emissions are generally released at both internal and external environments, and any measure to reduce the impact of a product on the external environment may result in negative effects on the working environment at the expense of human health [96,177,179]. To define, the relevant phrases as presented in the literature are referred. Compared to short and simple phrases adopted by other literature, [121] presents a more detailed remark, which can be adopted – the impacts of working environment can be defined as the effects on human health as a result of occupational exposures to biological, physical and/or chemical hazards at working environment during the life cycle of a product system. A comparison of literature is presented in Table 5, distinguished by sample groups in chronological order. The concept of existing methodologies is summarised as follows, also in chronological order:

(1) Direct-quantitative-and-qualitative approach by [177] where (i) death due to work related accidents; (ii) workdays lost due to wok related accidents and diseases; (iii) workdays lost due to illness; (iv) hearing loss; and (v) allergies, eczemas and similar diseases are identified as quantitative impact categories estimated based on organisational statistics data, together with (i) carcinogenic impact; and (ii) impact on reproduction being identified as qualitative impact categories and estimated based on semi-quantitative approach.

(2) A method to assess occupational health impacts is proposed by [180] based on DALYs, which takes account of number of morbidity, disability and mortality cases as well as the severity and duration of the incidents in terms of years of life lost (YLL) and years of life lived with disability (YLD). How to calculate DALYs per industry sector is outlined as a 5-step approach: (i) find out how many morbidity, disability and mortality cases there are; (ii) quantify how long each morbidity/disability case has been since the incidence; (iii) determine how severe each case is; (iv) determine what the upstream impacts associated with the sector are based on IO model; and (v) match the data on morbidity, disability and mortality with IO data.

(3) Built on EDIP methodology, a sector-based working environment assessment is proposed by [178] where a number of impact categories are identified, including total number of accidents, fatal accidents, central nervous system function disorder, musculoskeletal disorders, cancer, hearing damage, skin diseases, airway diseases (allergic and non-allergic) and psycho-social diseases. A five-step approach is suggested to calculate the number of injuries and accidents per unit weight of production: (i) identify sectors which show substantial rate of injuries and accidents; (ii) identify the corresponding products produced in these sectors; (iii) aggregate the number of all products; (iv) account for the work-related damages and injuries for the production activities based on statistics; and (v) determine the impact of working environment per functional unit, i.e. by dividing the outcome of (iv) by that of (iii).

(4) An impact assessment method for external and working environments is proposed by [179]. In relation to working environment, 2 impact categories i.e. occupational health (OH) and occupational safety (OS) are recommended where lost work days (LWD) is introduced as the category indicator for both categories. Data regarding the number of workers (i) affected by a particular hazardous item (WHI) and (ii) diagnosed suffering certain magnitude of disability (WMD) are required to estimate LWD for OH and OS impact categories, taking account of exposure, effect and damage factors whenever applicable. Meanwhile, DALY and potentially affected fraction (PAF) are adopted to assess the damage caused by the external environment to human health and ecosystem quality.

(5) The methodological framework developed by [181] aims to assess human health effects due to indoor and outdoor exposure to pollutants. The one-box model based on mass conservation and concentration homogeneity is selected as the default approach compared to the other 4 existing indoor air exposure models i.e. one-box model with mixing factor, multi-box model, two-zone model and eddy-diffusion model which are all compatible to USEtox model. The latter is used for assessing outdoor exposure assessment. In this case, characterisation factors for human toxic effects are calculated by determining the product of intake and effect factors.

(6) Two methods, i.e. Methods 1 and 2, are proposed by [182] to rank and identify chemicals to be included in LCA study. Based on USEtox model, Method 1 takes into account the concentration and severity of exposure, effect factors (EF) and the exposed population where the number of exposed personnel is applied as a weighting factor. Acting as a quality control tool, Method 2 is based on the risk quotient (RQ) as applied in occupational risk assessment, i.e. ratio of exposure concentration to occupational exposure limit. Data required for the assessment is collated from literature, toxicity report and databases. Characterisation factors in terms of DALY are then calculated by determining the sum of cancer and non-cancer effects.

(7) Work environment disability-adjusted life year (WE-DALY) is introduced by [96] which can be used to calculate the characterisation factors for the impacts on human health attributable to hazardous exposure in working environment. Using published statistics data for each industry, WE-DALY estimates the sum of the number of years of life lost (YLLn, representing the difference between the average lifespan of the workers and the actual age at death of the deceased worker) and the number of years of life lived with disability (YLDn, representing the duration of suffering certain injury or illness due to working environment).

(8) Work environment characterisation factors (WE_CF) by [121] is a continuation of the WE-DALY method developed by [96] to complement LCIA for the impact on human health attributable to work environment. WE_CF is determined as the ratio of WE-DALY to the physical output (e.g. mass and volume) produced by the industry.

An additional remark is that [179,121] have respectively classified existing approaches in line with chemical use/screening, work process and sector/compartment model; however, most of the literature is inaccessible (and therefore not further discussed here), which presents a possible reason why the impact(s) of working environment has been rarely included in LCA studies.

4.4. Interpretation – uncertainty and sensitivity analyses

In estimating potential environmental impacts, LCA, by its very nature, associates with uncertainties. Uncertainty is defined as the quantity discrepancy between the real values and the data used in the study [20] generally obtained from experiments, calculations, assumptions or estimations. Also, uncertainty can be defined quantitatively and qualitatively: the former is a measure which determines the spread of values attributed to a parameter while the latter refers to the lack of precision in data and methodologies due to incomplete data, lack of transparency, unrepresentative methods and the choice made [70]. According to [19], uncertainty is the 'lack of knowledge' with respect to true quantity value and model form, appropriateness of modelling and methodological decision, and therefore, its effects can be addressed by uncertainty analysis (UA) and sensitivity analysis (SA). This is in agreement with [7,70] in which UA and SA appear to be coupled to each other. Accordingly, UA is defined as a systematic technique which quantifies the uncertainty in LCI results due to variability and inaccuracy of data and model while SA is defined as a systematic technique which assesses the effects of methodological choice and data on the results [6,7].

To get a grasp of the state-of-the-art methodological development in this context, literature in Sample Groups A and B is analysed and the findings are presented in Table 6. In contrast to the vast number of literature recognising the inherent uncertainties in LCA (and the need to address them by performing UA and SA), the methodological concept in LCA context has not been widely covered. A few publications have attempted to explicitly classify the types of uncertainty; however, a common drawback is found as each list is limited to a few uncertainty types among many. Built on [6,7,9,12,19,20,70,73,80,83,124,130,139,147,148], all uncertainty types are integrated as illustrated in Fig. 9 to present an overarching scope.

Table 5
Comparison of literature on the impacts of work environment.

Phrase used	Proximity to impact of/from/in/to the work environment[a]	Level of detail[b]	Highlight of the literature [Resource]
Accidents; workplace exposure; working conditions	C	II, III	Working conditions is recognised as an environmental problem; accidents and working conditions are respectively discussed as process data and an impact category [134].
Accidents; work environment; impacts from the work environment	A, B	I	Toxic impacts of the work environment shall be assessed as a part of human toxicity impact category while non-toxic impacts of the work environment and those caused by accidents shall be further considered as separate impact categories [90].
Accidents	D	I	The impact category of accidents is usually not covered due to perceived marginal threat and difficulty in making any prediction [102].
Casualties due to accidents; impacts in work environment; chemical exposure at the workplace	A	I	The lack of standards leads to (i) indecisive situation if "casualties due to accidents" shall be considered as an independent category; and (ii) exclusion of "impacts in work environment" from further assessment [19].
Indoor and occupational exposure; injuries related to working environment accidents	B	II	Indoor and occupational exposure, including injuries (casualties) related to working environment accidents, is recognised as a new impact category undergoing characterisation model development—currently as a separate impact category but will become a part of human toxicity in future [139].
Indoor air; indoor chemical exposure; impacts to the working environment	A	III	A short summary is presented in relation to a few selected literature published between 1998 and 2009 in this context. It is noted that LCIA is available to assess human exposures to indoor chemicals as 2 relevant case studies have been reported [20].
Indoor air pollution	D	I	As an area of concern to many building occupiers, indoor air has become a special application of LCIA [8].
Indoor and occupational exposure	D	I	Rapid development of indoor and occupational exposure is noted [144].
Accidents	D	I	The development of some impact categories like accidents is poor as neither inventory data nor characterisation factors are available [151].
Work-related impacts; impacts to human health attributable to work-related exposures to workplace hazard; occupational health impacts from the work environment	A	IV and V	The "impacts to human health attributable to work-related exposures to workplace hazards" is expressed in terms of work environment disability-adjusted life year (WE-DALY), and its calculation is shown via a case study, which can be used for characterisation factor determination [96].
Working conditions	D	I	"Working conditions" is recognised as a social impact of a product system [25].
Impacts to human health attributable to the work environment; the work environment impact category; impacts from the work environment	A	IV and V	The work environment disability-adjusted life year (WE-DALY) of an industry is calculated with workplace data. Then, WE-DALY is used to determine work environment characterisation factors (WE-CF) [121].
Additional literature materials, i.e. Sample Group C:			
Impacts of the work environment; work-related accidents	A	IV	5 quantitative and 2 qualitative work environment impact categories are proposed. Data collection, reliability and relevance of these impact categories are discussed [177].
Occupational health impacts; health impacts due to hazardous work environments; workplace injuries; workplace-related illnesses	B	IV and V	A method to assess occupational impacts is proposed based on DALYs and an example is provided to show how the results of the model can be applied [180].
Working environmental impact; Occupational exposure; work-related damage; occupational accidents; occupational diseases and occupational injuries	A	IV and V	A method to calculate impacts of working environment per functional unit is proposed and its application is presented [178].
Impacts on the working environment; occupational health and safety; occupational health; occupational safety; occupational accidents; occupational diseases; occupational disabilities	A	IV and V	A new methodology is developed to assess the total impacts on the working and external environments and its applicability is shown in a case study [179].
Health effects from indoor pollutant emissions and exposure; human-health effects from indoor exposure; occupational exposure	C	IV and V	In line with existing model used for assessing outdoor emissions, the one-box exposure model is selected to determine the characterisation factors for human toxic effects due to indoor exposure [181].
Indoor occupational exposure; occupational health effects; occupational diseases; human-health impacts from indoor exposure	C	IV and V	In line with USEtox model, the indoor occupational priority list for LCA (OCPL-LCA, referred to as Method 1) is developed, which can be used for assessing human-health impacts attributable to indoor occupational exposures to solvents [182].

[a] Proximity to "impact(s) of work environment".
A Explicitly, if "impact(s) of/from/in/to the work(ing) environment" is mentioned.
B Implicitly, if "work(ing) environment" is mentioned.
C Loosely, if "workplace" is mentioned but not directly connected with the impact(s).
D Indistinctly, if neither work environment nor workplace is mentioned.
[b] Level of detail.
I Recognition only without discussion at LCI or LCIA level.
II Brief discussion at LCI level.
III Brief discussion on LCIA methodology.
IV In-depth discussion on LCIA methodology.
V Application/case study.

Table 6
The coverage of uncertainty, uncertainty and sensitivity analyses in literature.

Subtopic	Resources
1. Uncertainty	
• Recognition of uncertainty inherent in LCA[a]	[6–9,12,15–20,22–25,63,66,69–74,79,80,82,86,87,89,90,92,93,97,100–104,106,114,118,119,128–131,137–140,144,147,148,150,152]
• Definition[b]	[19,20,70]
• Types[c]	Explicitly: [12,19,20,70,80,124,139,147] Implicitly: [6,7,9,73,83,130,148]
• Sources[b]	[17,20,73]
• Problems[b]	[19]
2. Uncertainty analysis	
• Recognition of (the need for) uncertainty analysis[a]	[6–9,12,15,17,19,20,23–25,63,64,69,70,72,74,79,80,88–90,96,100–102,104,113,114,119,128–131,138,139,141,144,145]
• Definition[b]	[6,7,70]
• Methodologies[d]	[19,20,101]
• Methodologies specifically for LCI[d]	[7,70,73,79–81,124]
• Methodologies specifically for LCIA[d]	[115,118,124,150]
• Methodological concept[e]	[81,115,124]
• Application[f]	[115,124]
3. Sensitivity analysis	
• Recognition[a]	[6,15–20,23,72,73,76,79,80,89,101,102,128,138–140,147,148]
• Methodological concept[e]	[7,70,122,134,135]
• Application[f]	[1,6,7,70,122,134,135]

[a] Uncertainty (as is the need for uncertainty and sensitivity analyses) is recognised if it is only cursorily mentioned.
[b] Definition, sources or problems commonly associated with uncertainty is reported when discussion on the corresponding topic is unambiguously presented.
[c] The types of uncertainty is explicitly included if they are appropriately organised; or implicitly presented if one or more uncertainty types are unsystematically mentioned.
[d] Methodologies for UA and SA are covered if a suggestion(s) is made (without detail)—in the case of UA, the suggestion can be general or specific for addressing uncertainties at LCI or LCIA level.
[e] Methodological concept is proposed if the fundamental principle is discussed.
[f] Application is performed if the methodology is implemented and/or the results are shown.

As reported by [19,20,101], a range of approaches have been proposed for UA. [174,183–188] are included in Sample Group C to complement the analysis. The fundamental concept and application of the statistical, scientific, social/constructive and graphical approaches of UA in the context of LCA are discussed as follows:

(1) Statistical approach

(i) Stochastic modelling – to propagate uncertainty due to inaccurate data [188], input and output parameter uncertainty [184] and model uncertainty [101]. Stochastic modelling involves the use of

a. a probability distribution for different conditions [185]:

- uniform for less studied and/or more debated parameters
- normal if the input data are the average values of the data collected
- lognormal for skewed data limited to positive values only
- triangular for less studied and/or more debated parameters
- beta generally for several shapes of distribution bounded on both positive and negative sides where no prior knowledge is required
- gamma for model developed from real world samples

b. a sampling technique. The parametric sampling technique, e.g. bootstrapping as recognised by [20], is not included in this article as its methodological concept in LCA context for UA application is not found. Random and non-parametric sampling includes

- Monte Carlo [101,187,188]. Within a defined range, all parameters are varied and selected randomly by employing a computer. To deal with inaccurate data, all key input parameters are specified and applied one by one in the calculation. To deal with model uncertainty, characterisation factors are repeatedly calculated with all possible uncertainties. After an extensive number of repetitions, the results form a probability distribution where the statistic properties of the distribution are investigated. Monte Carlo is technically valid and widely recognised.
- Latin Hypercube [184,187]. This is a special type of Monte Carlo simulation which segments the uncertainty distribution into non-overlapping intervals (with equal probabilities). From each interval, a value is randomly chosen and substituted into an equation to obtain an output variable. The output variables generate a distribution with a representative frequency chart. The complex mathematic model of this sampling method presents a drawback and hinders its application.

(ii) Non-parametric good-of-fit test, e.g. Kolmogorov–Smirnov (K–S) test and Chi-Square test [124] – to choose the best hypothesised distribution. The frequency distribution of inventory data (with multiple parameters collected from industries or via simulation) and the probability density function of a hypothesised distribution (normal, lognormal, gamma, beta etc. generated by Maximum Likelihood Estimation based on the characteristics of parameters, i.e. mean, standard deviation etc.) are assessed by K–S and Chi-Square tests. A null hypothesis is set, i.e. both distributions are in consistency. A critical value is assigned to K–S and Chi-Square tests to decide if the null hypothesis is true at the significance level of 0.05. When the results of K–S and Chi-Square tests are in conflict (very uncommonly), apply K–S test for a small sample (with 30 data or less) and Chi-Square test for a relatively bigger sample. The lowest values of results from both tests indicate the best distribution of the inventory data.

(iii) Analytical method [185–187] – to propagate uncertainties due to input data on the model outputs. The relationship between input and output variables is evaluated by estimating the moments, i.e. variance or standard deviation of the distribution based on Taylor series. Although the analytical method requires less information regarding the distribution and is computationally efficient compared to sampling method, its application is practically hindered by the complexity of Taylor series.

(iv) Fuzzy number [79,81] – to propagate epistemic uncertainty inherent in matrix-based inventories by applying upper and lower limits to emission and resource flow inventory vectors to create a number of matrices. For the defined degrees of belief, i.e. α-cuts$=0,\ldots,1$, the matrices are solved. The inventory results at all α-cuts are combined to form a fuzzy distribution. The approach is advantageous as it is more informative and computationally efficient. It is claimed that a comparison between alternatives of epistemic uncertainties can be made by ranking the fuzzy numbers; however, no methodological concept is provided.

(v) Bayesian [183] – to estimate model uncertainties which propagate parameter uncertainties. A probability distribution is generated by applying stochastic modelling, i.e. select a

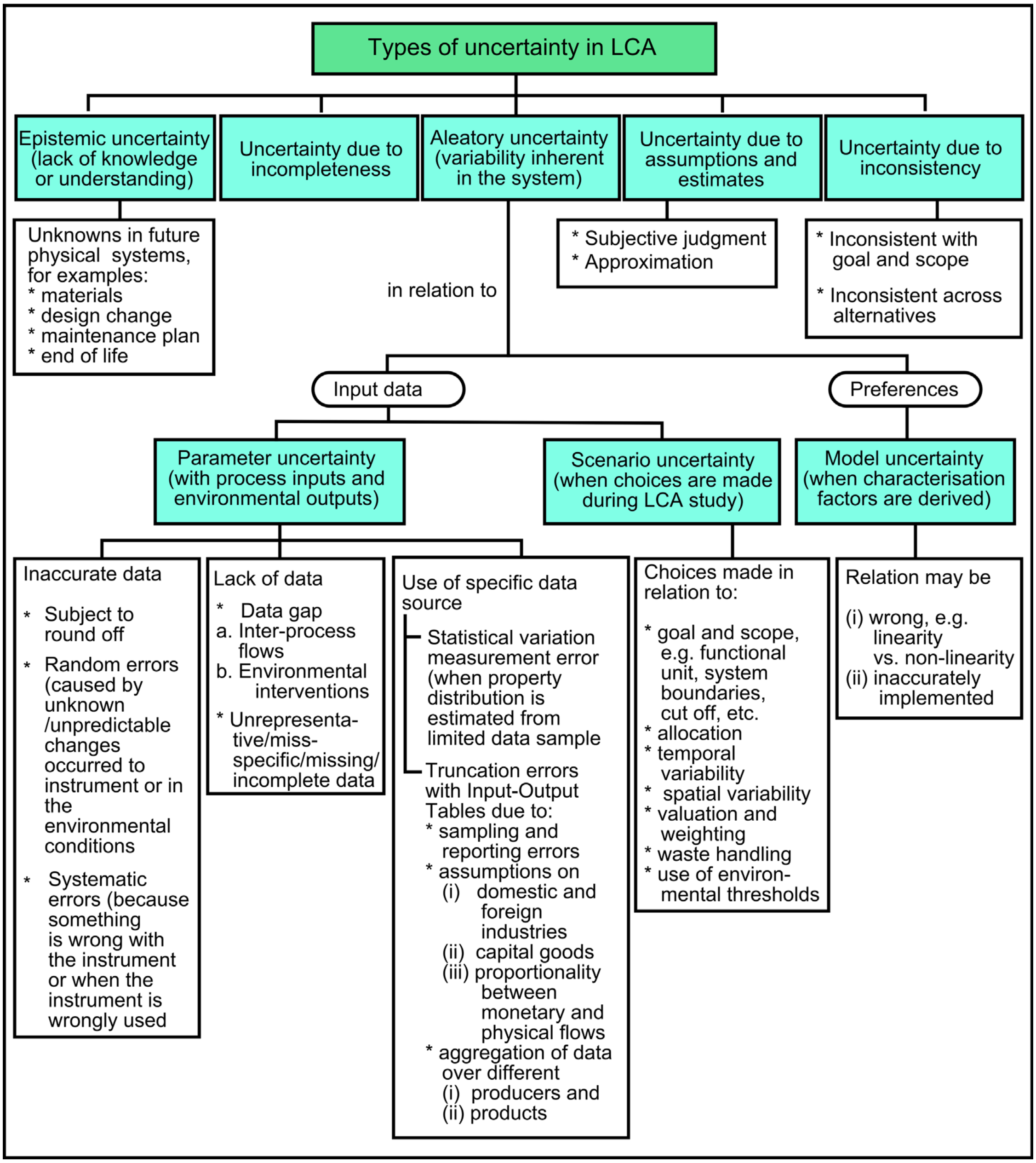

Fig. 9. Types of uncertainty inherent in LCA.

prior distribution type of uncertainties and employ Monte Carlo to calculate the indicator results of an impact category repeatedly. To measure the importance of each parameter uncertainty, the correlation coefficient between the input parameter and its outputs is calculated. A posterior probability is then formed by applying Bayesian update procedure. For each parameter, the ratio of standard deviation to means (known as the coefficient of variation) can be calculated to determine how much uncertainty is reduced.

(vi) Interval calculation [187]. A 95% confidence interval is generally calculated by using standard deviation in the analytical method and non-parametric good-of-fit test.

(2) Scientific approach

(i) More research [101] – to reduce model uncertainty. Carry out more scientific research for better measurements and more accurate data.

(ii) The scale of uncertainties [80] – to manage uncertainties at LCI level. After performing a hybrid LCI, uncertainties due to data, cut-off, aggregation, temporal and spatial factors are estimated so that ways for improvement can be identified by comparing the scale of uncertainties. Then, data of low relevance are replaced by data of higher quality, followed by estimation and comparison of the uncertainty scales, iteratively until the results are sufficiently certain. A critical issue with this approach exists as detail on estimating uncertainties is not provided.

(iii) Scenario comparison [101,186,187] – to investigate the effect of data and model uncertainties on the results via parameter variation (also known as scenario analysis). All parameters remain unchanged while one specific parameter (or a number of consistent scenarios of parameter e.g. best, worst and average cases) is varied. In addition, model uncertainty can also be dealt with by comparing the characterisation factors calculated from a few strategically manipulated uncertainty parameter values.

(iv) Uncertainty factors (UFs) to deal with

- unrepresentative input data due to future technology, temporal and geographical factors [188]. Based on empirical analysis of technological development, time series and cross-sectional data on process inputs and environmental releases, the UFs are estimated and applied to the unrepresentative input data.
- uncertainties due to parameters and choice [115,184]. UFs are used to characterise the parameter uncertainty of input data while stochastic modelling (i.e. Monte Carlo or Latin Hypercube simulation) is applied to quantify and propagate parameter uncertainty of the output variables into a particular distribution type. A comparison indicator can be used to compare the choice between 2 products.
- pairwise comparison of alternatives [174]. Based on the LCIA results for 2 scenarios for an impact category (in the form of crisp number, probability distribution function or fuzzy membership function), the preference relationships between scenarios (i.e. one scenario is preferred, strongly preferred, not preferred or strongly not preferred to the other) are evaluated and aggregated. The aggregated results of the preference relations for each couple of scenarios are used for the calculation of the classical entropy measure and an index; and accordingly, all scenarios under study can be ranked from the worst to the best or vice versa.

(3) Social/constructive approach [186,188]. Pedigree matrix is applied to qualitatively deal with uncertainties due to unrepresentative or unavailable data. This is done by identifying relevant data quality indicators, e.g. temporal, spatial and future technology correlations, at different levels. Accordingly, a score is assigned to each level, e.g. for temporal indicator, levels 1, 2 and 3 represent data age groups 0–3, 4–10 and 11–15 years respectively etc.. Expert judgment and/or inputs from stakeholders are required in defining the pedigree matrix and furthermore assigning the scores to indicate the level of each indicator applicable to the case under study.
(4) Graphical approach [185]. Some graphic tools including error bars, histograms, box-and-whisker plots (Tukey box), cumulative distribution functions and the graphs of mean outcome versus the number of iteration for modelling are used to visually show how certain/uncertain the results are.

In short, scientific approach by more research directly reduces uncertainties; scenario comparison and graphical approaches show the effects of inputs (e.g. parameters and choice) on the results; stochastic modelling, scale of uncertainties and UFs deal with uncertainties while analytical method, fuzzy number, Bayesian and hybrid LCI by nature propagate uncertainties.

SA also applies mathematics concepts (in addition to scenario analysis) to investigate the influence of methodological choice such as input data and assumptions on the result(s). Compared to ISO 14040 [6] which suggests SA as one of the reasons for the differences in LCIA results for alternative products, ISO 14044 [7] has put more emphasis on the use of SA to (i) check input and output data during LCI for significant environmental burdens and/or further system boundary refinement; (ii) obtain additional information for the reference choice during normalisation; (iii) assess the consequences of value choice during weighting; (iv) check for sensitivity and limitations of the study during interpretation; and (v) include mass, energy and environmental significance criteria in SA for a comparative study. Among review articles of Sample Group A as presented in Table 1, [9,16,18–20,24] have embraced the role of SA in LCA studies. Meanwhile, a constantly gradual (but not sufficiently detailed) development can be observed in the literature of Sample Group B from a very brief recognition [6,15–20,23,72,73,76,79,80,89,101,102,128,138–140,147,148] to a short discussion on the basic concept covering the use of reliability and validity analyses [134,135], percentage of change or the absolute deviation [7], and temporal sensitivity [122] as a measure for SA, possibly supported by the application of qualitative method (i.e. expert judgement) or quantitative methods including the use of spreadsheets, linear and non-linear programming [70]. In addition, SA has been performed in some LCA studies [1,6,7,70,122,134,135] but the applied methodologies have not been detailed. As a matter of fact, SA is not new and has been commonly applied in other fields, e.g. weather forecast, decision making and risk assessment, to name but a few. A number of common methodologies are preliminarily but not exclusively identified partially in accordance with [189,190] and categorised with a brief description as illustrated in Fig. 10, which can be seen as a connecting point for stimulating research development of SA in the context of LCA.

4.5. Research needs and areas for future development

Probably in response to a particular remark presented in ISO 14040 [6], '*there are no generally accepted methodologies for consistently and accurately associating inventory data with specific potential environmental impacts*' (page 16), selecting the best practice or recommended approach via comparison, harmonisation or consensus building has become common recently, as shown in Table S6 of the Supplementary material. In respect of this, [152] points out that consensus building is not practical due to the fact that existing methods under evaluation may have less scientific ground while new methodologies are constantly being developed, which would be excluded from such evaluation. As advocated by [152], LCA research shall focus on meeting the major challenges e.g. integrating global scale and spatial differentiation. Other unremittent challenges for future LCA development are identified via this analysis, as follows:

- LCI data – while LCI approaches are well developed, unavailable, missing, out-of-date and unrepresentative data have remained a major obstacle to deliver reliable LCA results. Research into developing robust and representative inventory is required.
- Classification involving series and parallel mechanisms – some elementary flows are attributable to more than one impact categories which are likely to be assessed in an LCA study. Relevant examples include, first, SO_2 which generally results in acidification, human toxicity and aquatic ecotoxicity [109]; and second, water which results in water deprivation [156] due to consumption and furthermore the depletion of water as a natural resource [26]. How to appropriately classify such elementary flows in series and parallel mechanisms shall be explored and developed.
- LCIA methodology – research on the impacts of water use, noise and working environment is still ongoing and shall be further expanded to cover comprehensive scope and take into account spatial and temporal dimensions. Other impact categories including space use, odour, non-ionising radiation (i.e. electromagnetic waves) and thermal pollution [134,144] have been noted but their characterisation model has not yet developed. At present, there is no environmental mechanism, indicator, characterisation factor and model available for these impact categories.
- Uncertainty and sensitivity analyses – in relation to UA, methodology that can be applied to address uncertainties due to incompleteness and inconsistency has not been explored. Also, how to incorporate existing methodologies for SA, for example advance statistics, into LCA study shall be further studied.

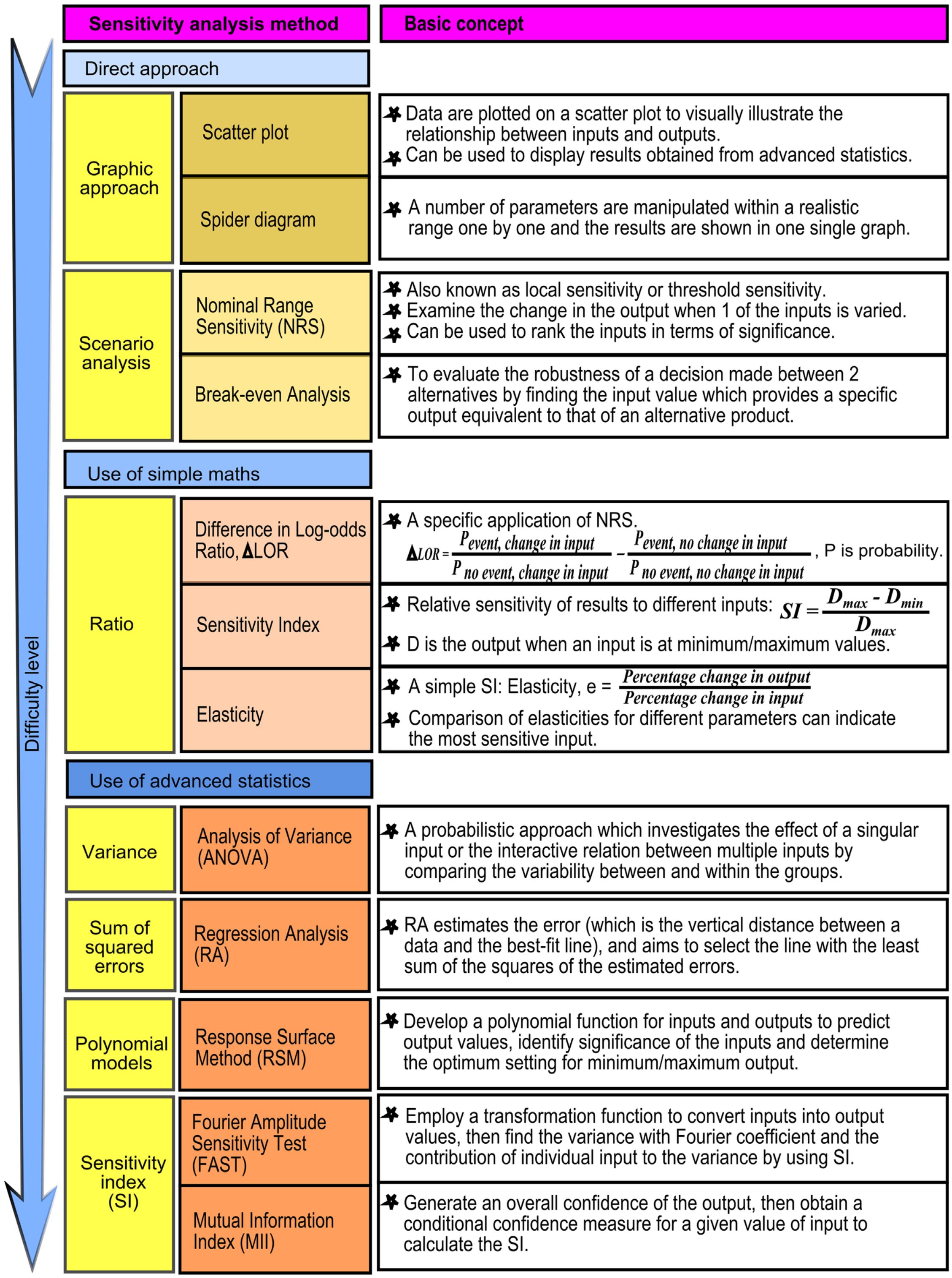

Fig. 10. The basic concept and difficulty level of some common SA methods.

- Any other relevant topics – other elements which are not explicitly included in ISO Standards, for example rebound effects, renewability of resources, dynamic of environment and future scenario modelling, are of increasing importance from pragmatic perspective. Indeed, dealing with rebound effects or renewability as well as modelling dynamic environment or future scenario are challenging and require extensive research engagement to overcome its complex nature.

5. An LCA framework for marine PV systems

In this section, the focus is on proposing an LCA framework for marine PV systems based on literature analysis presented in earlier sections, existing reviews [46–48] and ISO Standards [6,7]. Hence, LCA framework and studies discussed in this section are pertinent to marine PV systems and for brevity, they are respectively referred to as *LCA framework* and *LCA study* or *the study*.

Table 7
Impact categories caused by a marine PV system if assessed by CML, Eco-Indicator 99 or ILCD in descending order, with estimated order of magnitude and identified key elementary flows or processes.

Impact category, unit	Order of magnitude[a]	Key elementary flows or processes[a]
CML[b]		
Marine Aquatic Ecotoxicity Potential, kg DCB-equivalent	8	• Disposing metallic, glass, plastic and packaging paper scrap to incineration plant • Disposing metallic and polystyrene scrap to landfill
Freshwater Aquatic Ecotoxicity Potential, kg DCB-equivalent	6	• Disposing metallic scrap to incineration plant • Disposing plastic scrap to landfill
Global Warming Potential, Including/Excluding Biogenic Carbon (GWP 100 years), kg CO_2-equivalent	4	• Glass and silicon respectively required for PV module fabrication and cell manufacturing • The fabrication process
Human Toxicity Potential, kg DCB-equivalent	4	• Glass and silicon respectively required for fabricating PV modules and manufacturing cells • Disposing metallic, plastic and electronic scrap to incineration plant
Acidification Potential, kg SO_2-equivalent	2	• Glass required for PV module fabrication
Terrestric Ecotoxicity Potential, kg DCB-equivalent	2	• Disposing metallic scrap to landfill
Photochemical Ozone Creation Potential, kg Ethene-equivalent	2	• The fabrication process
Eco-Indicator 99[c]		
Ecosystem Quality – Ecotoxicity, PDF$*$m^2$*$a	5	• Disposing metallic scrap to incineration and landfill
Resources – Minerals, MJ surplus energy	4	• Tin and copper required for PV modules and inverters
Ecosystem Quality – Acidification/Nutrification, PDF$*$m^2$*$a	2	• Glass required for PV module fabrication
Ecosystem Quality – Land Use, PDF$*$m^2$*$a	2	• PV cell factory • Regional storage of tin
ILCD[d]		
Ecotoxicity for Aquatic Fresh Water, CTUe	7	• Disposing metallic, plastic, electronic and glass scrap to incineration plant • The fabrication process • Disposing metallic and plastic scrap to landfill • Use of silicon for PV cell manufacturing
IPCC Global Warming, Including and Excluding Biogenic Carbon, kg CO_2-equivalent	4	• Glass required for PV module fabrication • The fabrication process • Disposing plastic scrap to incineration plant
Total Freshwater Consumption, Including Rainwater, kg	3	• Tap water consumed during manufacturing and recycling processes
Photochemical Ozone Formation	2	• The fabrication process
Terrestrial Eutrophication, kg NMVOC, mole of N-equivalent	2	• Glass required for PV module fabrication • Dismantling PV system • Use of silicon for PV cell manufacturing
Acidification, mole of H^+-equivalent	2	• Glass required for PV module fabrication

[a] Based on cradle-to-grave LCA case studies recently completed by the corresponding author. The PV system has a power of 288 kW_p, consists of 1176 poly-crystalline modules and is designed for a RoRo cargo ship over a 30-year lifespan. However, the case studies are not the focus of this article, and therefore are not further elaborated here. The order of magnitude of any number between 1.00×10^8 and 9.99×10^8 is 8. The list of key elementary flows and processes for each impact category starts with the most significant one.

Other impact categories, as below, are not shown due to their negligible values:

[b] Abiotic Depletion, Eutrophication Potential, Ozone Layer Depletion Potential and Terrestric Ecotoxicity Potential.

[c] Ecosystem Quality – Land Conversion; Human Health – Carcinogenic Effects, Climate Change, Ozone Layer Depletion and Respiratory (Organic and Inorganic); and Resources – Fossil Fuels.

[d] Freshwater Eutrophication; Human Toxicity, Cancer and Non-Cancer Effects; Ionising Radiation; Marine Eutrophication; Ozone Depletion; Particulate Matter/Respiratory Inorganics; and Resource Depletion, Fossil and Mineral.

5.1. Goal and scope definition

In compliance with ISO Standards, the *LCA framework* consists of four life-cycle phases, which begins with goal and scope definition. The reason(s), application, audience, use of the results and intention of public disclosure, which are required for goal definition, are directly subject to *the study*. In relation to scope definition, some elements are contextual but others are homogenous (i.e. similar across all *LCA studies*), as follows:

- Product system to be studied: PV system(s) installed onboard a marine vessel (with details of PV module type, number and power output). Existing PV module types for onshore applications i.e. thin film, amorphous, mono- and poly-crystalline are suitable for marine operation. In implementing a marine PV system, strong wind, humidity, salt, limited area for installation and shading issue, as discussed in [191], are additional technical aspects to be considered by design engineers. From an LCA perspective, marine PV systems differ from onshore systems in one aspect i.e. the need of coated or galvanised metallic parts.
- Function: to augment/fully supply power required for operation and/or propulsion for a large/small marine vessel. It is worth noting that the function of a marine PV system varies with vessel size (and type). The implementation of PV system(s) onboard large vessels such as general cargo ships, tankers, bulk carriers, liquefied gas carriers, container ships, passenger and vehicle carriers etc. can only augment auxiliary power supply, although the PV technology of today has shown the capacity of fully powering smaller vessels such as boats, barges and catamarans.
- Functional unit: operation of the PV system(s) throughout the life cycle of a marine vessel i.e. 25–35 years for a particular sailing profile, for example transiting oceans by large vessels or along waterways by small vessels.
- Reference flow: power generated by marine PV system(s) throughout the life cycle of a vessel which is equivalent to that supplied by an alternative system operating on the same vessel type and sailing profile. Reference flow is only required for a comparative study where a conventional technology is likely to be chosen as the reference case, i.e. diesel engines for large vessels and motors for small vessels.

- System boundary: components and life cycle phases to be studied. A marine PV system consists of PV modules, balance of systems (BOD), support structures, inverters and transformers, in addition to auxiliary devices such as maximum power point tracking control system, diodes, wiring and distribution bus. Quantity of individual components is subject to technical requirements, e.g. design, power output, efficiency, solar radiation, lifespan etc., which are determined by design engineers using commercial software. Meanwhile, LCA practitioners decide whether or not auxiliary devices are within the system boundary based on the preliminarily established cut-off criteria. Factors to be considered as cut-off criteria include system contents (such as technological, social and economic values), stream types, mass percentages, data availability, energy, toxicity and relative contribution to the functional unit, as reported in Section 4.1. *The study* can be of cradle-to-grave, cradle-to-gate, gate-to-gate or gate-to-grave. The cradle-to-grave *LCA study* considers a full life while the others focus on one or more phases from energy and raw material acquisition, wafer production, cell manufacturing and module fabrication, installation, operation and maintenance to end of life where transport is inclusive if applicable. See [48] for detailed manufacturing processes.
- Allocation: avoidance of data distribution via system expansion and subdivision. Allocation is recommended for large vessels due to the involvement of diverse components and variation in their lifespans, for instance 20–30 years for PV modules and 10 years for inverters. System expansion is applied when an additional number of components with shorter lifespans (which is necessary to fulfil the functional unit) are included as a part of *the study*. To apply subdivision, input and output data involved in individual processes at each phase, in particular during manufacturing and end of life, are compiled.
- Assumptions: inferences made for uncertain or unavailable background information and technical aspects. Making assumptions is inevitable and disclosure is required in *the study* for transparency.
- Requirements on data and quality: provision made for data types, sources, completeness and reliability. Technical data (including PV array design specifying rigid or flexible panels assembled from PV modules in series or parallel, maximum areas available for installation, solar radiation, energy input and output etc.) and LCA data (such as material types, mass breakdown, energy and water consumption, final product(s), emissions and wastes etc.) are both required. Data can be of primary and secondary sources, i.e. measured in laboratory, calculated from formulas, modelled using simulators, estimated based on expert judgement, published in journal articles, industrial reports, government documents and textbooks or presented in conferences or databases. Complete and reliable data are always expensive and not readily available but preferable for decent research outcome.
- LCIA methodologies and impact categories: characterisation models and relevant impact categories to be applied. A number of characterisation models can be considered, including ILCD, CML and Eco-Indicator 99, to name but a few. Impact categories defined by these characterisation models vary from one to another, as do their corresponding category indicators and the underlying LCIA methods. Both category indicators and the underlying LCIA methods are chosen by default when a characterisation model is selected for an LCA application.
- Optional elements: inclusion (or exclusion) of normalisation, grouping and weighting in *the study*. Indicator results are *normalised* when they are compared to a reference i.e. a particular input or output in a base case scenario or on a local, national, regional or global scale. Grouping can be either *sorting* or *ranking* where impact categories are respectively organised based on a nominal value or a predetermined scale. Weighting results are the products of weighting scores and indicator results (with/without normalisation), which can be discrete for individual impact categories or aggregated across impact categories. The outcome of ranking and weighting is subjective due to the involvement of value choices; and therefore their presentation shall be supplemented with indicator results for individual impact categories.
- Value choices: use of expert judgement or personal preference. Due to time and resource constraints, how to proceed is always determined based on technical background, experience or personal choice. For example, it is a value choice to decide
  (i) which value (e.g. lowest, average or highest) to use if a range of the values is reported. For instance, the lifespan of a marine PV system, knowing that marine vessels and PV modules respectively have a life span of 25–35 years and 20–30 years.
  (ii) which alternative to select, if multiple options are possible to meet the technical requirements. For instance, design layout of marine PV system – single- or multiple-array.
  (iii) which characterisation model(s) to apply etc.
- Options that are available and why a particular decision is made in *the study* shall be reported, as value choices result in subjective outcome.
- Limitations: restricted areas, from an LCA perspective, which are not addressed in *the study* due to technical issues, limited time and missing/unavailable data. Such limitations shall be transparent.
- Life cycle interpretation: analyses of the results, data quality, assumptions and value choices. In addition to presenting LCI and LCIA results, conclusions and recommendations drawn from the analyses based on assumptions and value choices shall be outlined.
- Use of critical review: appraisal to be carried out by experts or not. Aiming to verify consistency in data, methodology, interpretation and reporting, a critical review, preferable by an external party, is required if *the study* presents an assertion to the public after comparing 2 product systems, e.g. marine PV system versus conventional technology.
- Report requirements: expectations on report format and contents. In the form of soft or hard copy, some common examples of report format to consider include technical report, text book, handbook, poster, conference paper and journal article. The mandatory elements of an LCA study, together with assumptions and limitations, shall be comprehensively covered.

5.2. LCI analysis

The elementary flows of the product system are collected, estimated and standardised during LCI analysis. As discussed in Section 4.2.1, LCI approach determines the data type required for *the study*, i.e. attributional approach necessitates average data while consequential approach involves marginal data. Both approaches are technically applicable and the choice shall be made based on the reason(s) of performing *the study*, in agreement with the defined goal and scope. Attributional approach is appropriate if *the study* aims to estimate the environmental burdens of a marine PV system onboard a small or large vessel. Consequential approach shall be applied if *the study* aims to investigate market and non-market effects of implementing marine PV system which reduces (or eliminates) the role of conventional technology in marine industry. The LCI principle, including process based (using process flow diagram and matrix), fuzzy matrix, IO, tiered hybrid, IO based hybrid and integrated hybrid approaches as presented in Section 4.2.2, shall be selected in line with the defined goal and scope of *the study* where time and resources, in particular data availability and expertise, are the key factors to consider. The strengths and limitations of these principles presented in Table 3 can be useful in making the decision.

Relevant data in this context include lifespan, energy consumption and emissions, as follows:

- The lifespans of amorphous, mono- and poly-crystalline PV systems range between 20 and 30 years while their greenhouse gas (GHG) emission rates are 15.6–50.0, 44.0–280.0 and 9.4–104.0 g CO_2-equivalent per kW h_e respectively [46].
- As reported by [47], manufacturing modules, BOS as well as inverters and installing an onshore PV system (with a power rate of 200k W_p consisting 850 poly-crystalline modules and occupying an area of 1649 m^2) consume approximately 4.59×10^6, 10.96×10^4, 3.02×10^4 and 8.96×10^4 MJ of energy respectively. Total emissions include 266806.4 kg of carbon dioxide, 1042.8 kg of methane, 1802.12 kg of nitrogen oxides, 2889.66 kg of sulphur oxides, 546.89 kg of carbon monoxide, 57.72 kg of particulate matter, 0.13 kg of lead and 541.52 kg of hydrocarbon.
- According to [48], 811–3150, 2860–11,673 and 2699–5150 MJ of energy are required for manufacturing 1 m^2 of thin-film, mono- and poly-crystalline PV modules respectively, covering processes from silicon feedstock preparation, wafer production, cell manufacturing, module assembly to framing (whichever relevant). Meanwhile, manufacturing 1 m^2 of BOS component requires up to 1930 MJ/kW and 34 MJ of energy for inverters and installation respectively. GHG emissions released during manufacturing phase in Western Europe and Hong Kong are 0.48–0.53 and 0.671 kg CO_2-equivalent per kW h respectively.

5.3. LCIA

The impacts caused by a marine PV system to the environment are assessed in LCIA. In consistency with the defined goal and scope and based on LCI results, 3 steps are taken for LCIA, namely (i) selection i.e. select relevant impact categories and characterisation model(s); (ii) classification i.e. assign LCI results to appropriate impact categories; and (iii) characterisation i.e. calculate category indicator results. To ease the tasks, a commercial LCA software e.g. SimaPro and GaBi can be employed, as currently practised by many LCA researchers. Impact categories attributable to a marine PV system as well as the LCIA results are expected to be different when diverse characterisation models are employed, as exemplified in Table 7. It is important to note that impact categories that are recently developed such as the impact of water use, noise and working environment, as discussed in Section 4.3, are likely not yet incorporated into existing LCA software. These impact categories can be of interest if *the study* intends to compare between a marine PV system and a conventional technology. See Section 4.3 to get more insights.

5.4. Life cycle interpretation

When results from LCI and LCIA are interpreted, significant issues shall be identified, uncertainties inherited in *the study* shall be addressed via UA and SA, and consistency as well as completeness shall be verified prior to drawing conclusions and making recommendations. To quantify uncertainty due to inaccuracy, adopt scientific approach for UA in *the study*: perform (i) more research if primary data are collected and (ii) scenario analysis if LCIA is carried out using an existing LCA software. If a characterisation methodology is to be developed for *the study*, apply any advanced technique such as stochastic modelling, nonparametric good-of-fit test, analytical method, fuzzy number, Bayesian, interval calculation, scale of uncertainty and uncertainty factors, as presented in Section 4.4. In either case, the results can be visualised using graphical approach. To assess the effects of methodological choice and data on the results, SA can be performed using direct approach (i.e. graphic approach and scenario analysis), simple maths based on ratio concept or advanced statistics such as ANOVA, RA, RSM, FAST and MII, as illustrated in Fig. 10.

6. Conclusions

It is argued at the beginning of this article that it would be intriguing to find out if LCA methodology is mature. The need of an up-to-date analysis on LCA methodology development embracing all life-cycle phases has been intensified by existing review articles on conventional LCA. The threefold analysis carried out here presents the first attempt ever made to review existing review articles, integrate and/or compare the findings with those of other literature types (mainly journal articles) on a particular topic and clearly show research development trend in a chronological order. The work demonstrates that literature analysis can be applied in a comparative, interesting and practical way. It is believed that the threefold analysis approach presented in this article can enhance the research quality of a wider research community as well as stimulate the understanding of readers. The findings suggest that methodology development on conventional LCA is extensive; but still, it is not thoroughgoing yet, as evidenced by the impacts of water use, noise and working environment as well as uncertainty and sensitivity analyses. Some topics are recognised but have not been explored or developed, for example, classification involving serial and parallel mechanisms and characterisation model for other impacts including space use, odour, non-ionising radiation and thermal pollution. Besides, other topics are also relevant, e.g. rebound effects, renewability of resources, dynamics of environment and future scenario modelling, and shall be further researched. Practical applicability of the findings on LCA methodology development is demonstrated by proposing an LCA framework for marine PV systems, which are the state-of-the-art development of renewable and sustainable energy in marine industry.

Acknowledgement

The work presented in this article is delivered as a research outcome of two projects, namely INOvative Energy MANagement System for Cargo SHIP (INOMANS²HIP funded by European Commission, Grant agreement no. 266082) and the Sustainable Thermal Energy Management Network (SusTEM funded by the Research Councils UK Energy Programme, EPSRC Reference: EP/K039377/1).

Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.rser.2015.12.058.

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